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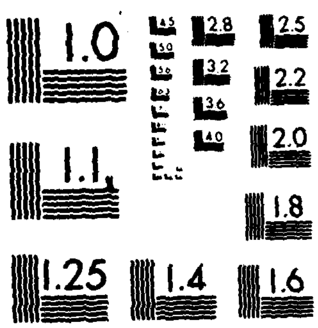

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December 1983

TLINES: A Computer Program for Circuits of Transmission Lines

by George A. Huttlin
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U.S. Army Electro[illegible]
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TLINES, a FORTRAN program installed on the PDP-11/60 computer at the Harry Diamond Laboratories Aurora Facility, is specifically designed for transmission-line circuit calculations on a small computer. Detailed step-function waves originate as exact solutions for a chosen initial charge distribution. Lumped inductances and capacitances are modelled as transmission-line segments. Data are input interactively, and the output consists primarily of plots on a graphics terminal of current, voltage, power, and energy as functions of time at various positions in the circuit and plots of current, voltage, and power as functions of position at given times. The program has provisions for (1) closing and opening switches, (2) series and parallel resistances between

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20. ABSTRACT (Cont'd)

transmission lines, and (3) series and parallel connections of transmission lines. Discussed are the basic theory relevant to the program, the construction of the program, instructions for the use of the program, and examples of its use.

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1. INTRODUCTION

Large pulsed-power machines--such as the Aurora Facility and the High Intensity Flash X-Ray Facility (HIFX) at Harry Diamond Laboratories (HDL)[1]--can be analyzed by circuits of transmission lines. Switches between the elements simulate the effect of spark-gap closure, and resistors account for relativistic diodes to the extent that they are described by a constant resistance.

In 1975 a computer program specificially designed for this type of circuit analysis was supplied to us by J. D. Shipman of the Naval Research Laboratory, where, under the auspices of the Defense Nuclear Agency (DNA), it had been written by J. P. Boris and based on the algorithm used by W. H. Lupton.[2] At HDL we expanded the program and put it into a form for interactive use on the IBM 370/168 computer via a Tektronix graphics terminal.

In the spring of 1982 we installed a completely rewritten version of this program on the PDP-11/60 minicomputer at the HDL Aurora facility. In this new version, the size of the program was reduced from the 1 mega-byte often required with the IBM 370/168 version to 64 kilo-bytes. This reduction was permitted by making all transmission lines in the program a single length equal to the time step DT. Circuits of lines of various lengths are handled by stringing together many short lines, with the assumption that each of the longer lines has a length approximated as an integral multiple of DT. As a result, the time dimension in all the arrays of the original program is eliminated, but more lines are required. The present version is dimensioned for 400 lines. As the program steps through time, data for time-dependent plots are stored in files from which they may later be retrieved for display.

Calculations are made at each junction for which data are generated. Since there can be up to 400 junctions equally spaced, there are sufficient data at each time step to provide a snapshot of the voltage, current, and power waves as they appear distributed throughout the circuit.

In TLINES, transmission lines are strung together with both a series resistor and a parallel resistor to ground at each junction. (The parallel resistors may be used to simulate lossy lines.) There are two types of special junctions of transmission lines. With one type, the parallel junction, one voltage is common to all three lines at the junction, and the currents add. With the second type, the T junction, it is the current that is common to all three lines and it is the voltage which adds. In the present version, there can be up to nine junctions of each type in the circuit. There are four types of switches in TLINES, each of which can be specified at any nine junctions. These switch types are (1) closure governed by voltage, (2) closure governed by time, (3) opening governed by current, and (4) opening governed by time.

The program is structured for interactive use by the operator, who is prompted by the computer for all input. The structure is outlined in menus, from which the operator chooses what he would like to do. These choices lead to submenus from which the program returns to the calling menu. The circuit data, once entered, can be stored in one of nine permanent files from which they can be retrieved for later study. (Appendix A contains a list of all files needed for the PDP-11/60 installation of TLINES.)

At time zero, all currents in the lines are assumed to be zero and each transmission line is specified to be charged to a particular voltage. To correct what would otherwise be a voltage discrepancy at junctions of lines charged to different voltages, traveling waves originate at these

[1]*Franklin J. Sazama and Alexander G. Stewart, Design and Testing of a Current and Voltage Monitor for HIFX, Harry Diamond Laboratories, HDL-TR-1558 (August 1971), 50-62.*

[2]*J. K. Burton, J. J. Condon, M. D. Jevnager, W. H. Lupton, and T. J. O'Connell, The TRITON Electron Beam Accelerator, Proceedings, 5th Symposium on Engineering Problems of Fusion Research, Princeton (1973), IEEE Cat. No. 73CH0843-3NPS-613.*

junctions. The waves subsequently propagate throughout the circuit according to the mathematics of reflection from and transmission across the junctions.

Lumped inductance or capacitance in a circuit is modelled as a single transmission line: a high impedance line simulates inductors; a low-impedance line simulates capacitors. The transmission lines themselves have no distributed resistance or conductance; however, such effects can be handled using the resistors between the lines.

2. THEORY

For transverse electromagnetic (TEM) modes in transmission lines, voltage steps of magnitude V can propagate through a transmission line in either direction with a speed v given by $v = (L_0C_0)^{-1/2}$, where L_0 and C_0 are, respectively, the inductance and capacitance per length in the transmission line. Since the propagation of a step in voltage implies a change in the charge density left in the wake of the voltage step, a current carrying the charge must accompany the propagating step. This current, I, is related to V by $V/I = Z = (L_0/C_0)^{1/2}$. Z is the characteristic impedance of the transmission line. If a voltage, V, is applied at the input of an infinitely long transmission line, a current of magnitude $I = V/Z$ is drawn into the line, and the transmission line appears at its input as a resistance with the value Z. Similarly, a resistor behaves as an infinitely long transmission line; the energy which is dissipated thermally in the resistor appears as an electromagnetic field which is lost propagating along the infinite transmission line.

A snapshot of the voltage configuration in a real transmission line is generally not the idealized step function. Voltage through a transmission line can have any functional dependance on distance along the line. However, since this program analyzes circuits of discrete transmission lines of constant impedance and a single length, and these lines are initially charged to static voltages, all waveforms in the analysis have a step-function character with steps of length DT*v.

In figure 1(a) are pictured four transmission lines. The left two of these lines are initially charged to a voltage V_0; the right two are initially uncharged. A switch can be imagined to separate the charged from the uncharged lines, and this switch closes at time $t = 0$. The voltage has the time-dependent profile as shown in the four snapshots of figure 1(a). Each of these profiles can be envisioned to be the result of the superposition of two waves of height $\frac{1}{2}V_0$ propagating in either direction, as illustrated in figure 1(b). An alternate decomposition of the profiles of figure 1(a) is illustrated in figure 1(c). This latter view incorporates explicitly in the formulas the voltage $V_0(N)$ to which each line N was initially charged, and it is this view that is used in TLINES. This is also the view taken in the original version.

Because of its constant impedance, nothing of interest to the calculation happens within a transmission line. It is at each junction, where a line of one impedance meets a line of possibly another impedance, a resistor, or perhaps several lines, that a right-going wave, for example, gives rise to a left-going wave. Therefore, it is only at two junctions that TLINES need keep track of the wave heights. These right- and left-going voltage heights at each end of each transmission line are stored in the program in arrays named as follows:

VPXP ... right-going (**V**elocity **P**ositive) wave in the right end (position **X** **P**ositive)

VMXP ... left-going (**V**elocity **M**inus) wave in the right end (position **X** **P**ositive)

VPXM ... right-going (**V**elocity **P**ositive) wave in the left end (position **X** **M**inus)

VMXM ... left-going (**V**elocity **M**inus) wave in the left end (position **X** **M**inus)

The initial values V_0 are stored in the array VXP. If we use these wave heights, the voltage in the right end of the Nth line is given by VXP(N)+VPXP(N)+VMXP(N), and in the left end the voltage is given by VXP(N)+VPXM(N)+VMXM(N). On the other hand, the current near the right end of a line is given by the difference (VPXP(N)−VMXP(N))/Z(N), while the current near the left end is given by (VPXM(N)−VMXM(N))/Z(N).

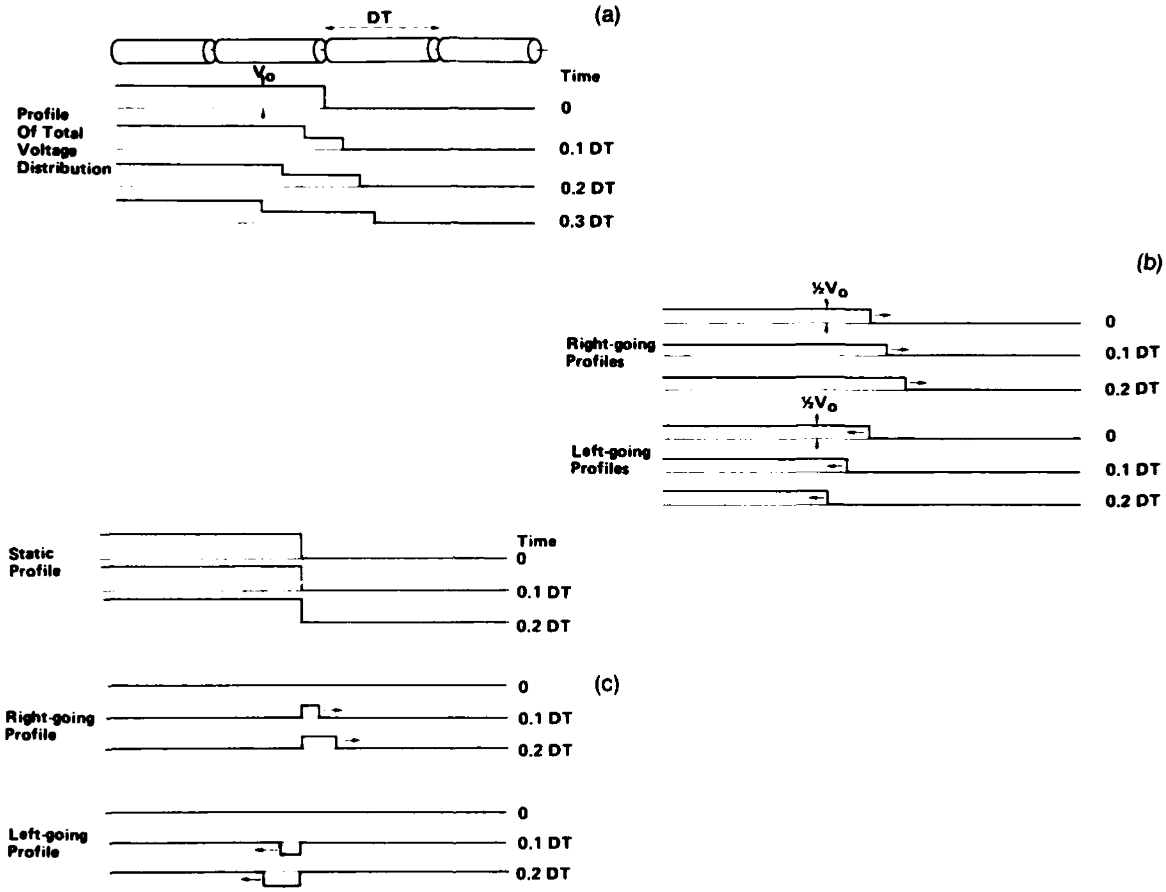


Figure 1. Voltage profiles of TLINES circuit.

The operation of the program proceeds as follows: initially, the heights of the four moving waves are considered throughout the circuit to be zero, in keeping with the convention shown in figure 1(c). However, an initial voltage imbalance such as shown in figure 1(a) cannot be sustained. To rectify this imbalance, waves leaving the junction are generated. In their wake these waves leave continuous voltage and continuous current across the junction. These conditions are simply an application of Kirchoff's laws as is detailed in appendix B. At the instant of the next step in the program, a time DT later, these waves arrive at the junctions at the opposite ends of their respective transmission lines. In the language of the program, VMXP(N) from the step NSTEP in line N gives its value to VMXM(N) for the step NSTEP+1 in the line N; similarly, the value of VPXM(N) becomes the value of VPXP(N). At this next step the program takes the waves arriving at each of the junctions in conjunction with the static voltages and solves for the pair of waves departing from each junction such that Kirchoff's laws remain satisfied, etc. (Once a wavefront arrives at a junction, that front's height—say VPXP(N)—gives the height of the wave at that junction until the next time step, at which time a change in height arrives.)

The general flow of the calculation can be represented by figure 2. In this figure the circuit is shown at several time steps in the calculation. Connecting the junctions from one step to the next are arrows representing the traveling waves. The arrows are illustrated as solid lines and as dotted lines to illustrate the existence of two independent sequences of calculations making up the overall calculation. The waves represented with solid lines do not interact arithmetically with those represented with the dotted lines. The common bond of these two independent webs is in the initial static voltages that bound the calculation in time. (This situation of independent webs mapping the progress of the calculation through time/position space could also arise in the old form of the program TRANS, even when lines of differing lengths were incorporated into the circuit.)

The coding of the calculation is contained in subroutine CALC, which is given in appendix C.

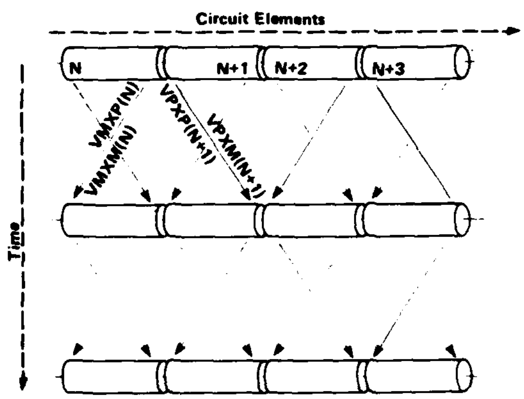


Figure 2. Interrelation of successive calculations.

3. CODING THE CIRCUIT

3.1 *Units*

One may choose any consistent set of units for use with TLINES. Since the output is listed with exponential notation, there is no format problem with numbers of extreme magnitudes. You can enter the data, for example, in units of seconds (for DT), ohms (for the Z's) and volts (for the VXP's), and the output will be consistent with current in amps, power in watts, and energy in joules. However, in the pulse-power business, a more appropriate set of units would be nanoseconds, ohms, megavolts, mega-amps, terawatts, and kilojoules. The capacitances and inductances listed in the output would then be in nanofarads and nanohenrys, respectively.

3.2 *Normal Junctions*

Basically, the circuit is expressed in terms of transmission lines numbered from 2 through CAPM, connected in numerical sequence as in figure 3. Line 1 is a dummy element disconnected from line 2 and the rest of the circuit. Lines 2 through CAPM can each be set to any impedance the user desires. Line CAPM+1 is a zero-impedance line that can be used if so desired. Note that the junction between element N and element N+1 is denoted junction N. At each junction are two resistors, RH and RG, which are numbered as is the junction. RH connects the center conductors of the two transmission lines and RG connects the center conductor of the N^{th} transmission line to ground. The default value for each of the resistors RH is zero, and the default value for each of the resistors RG is 9.99×10^{20} ohms. The user can choose to alter any of these resistors RG and RH that he wishes.

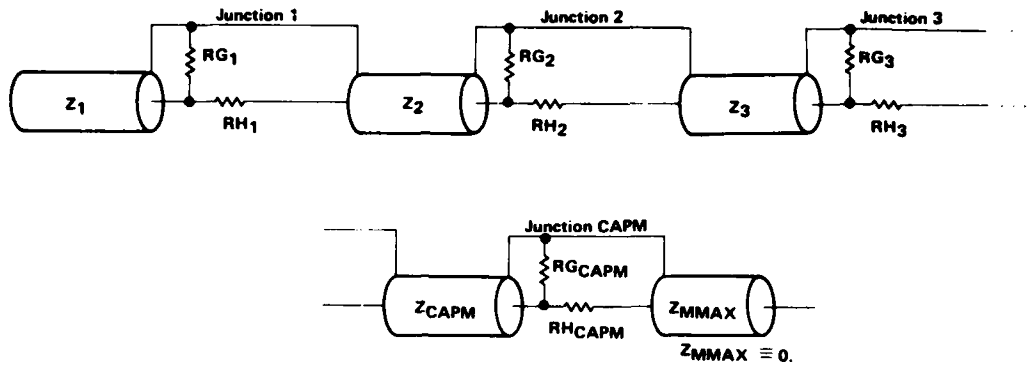


Figure 3. Basic sequence of elements in TLINES circuit.

3.3 *Special Junctions*

In addition to the standard connection of lines in figure 3, three lines can be joined in either of two ways. The first of these is shown in figure 4 and will be referred to as a parallel junction: at the junction the voltage across each of the lines is the same and the current splits. We will refer to the second of these special junctions as a "T" junction, which is shown in figure 5. At the "T" junction it is the current which is common to each of the lines, and the voltage divides. Note the identifications of the lines in figures 4 and 5. In each case two of the lines are numbered consecutively. The first of the consecutively numbered lines is designated MP or MT for parallel or "T" connections, respectively. The third line at the junction is designated MPF or MTF. Note in particular the interconnection of shield and center conductors for the "T" junction and the relation of this convention to the elements designated as MT and MTF. The program is dimensioned for up to nine of each of these two types of special junctions, and the user will be asked by the program to identify the line number for each of the nine MP's, MPF's, MT's, and MTF's that are needed in the circuit. The choice of the particular value of the index (1 through 9) is arbitrary. The default value of MP, MPF, MT, or MTF is 1. Parallel and "T" junctions will be further clarified later (fig. 7).

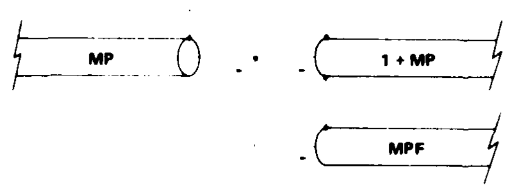


Figure 4. Parallel junction.

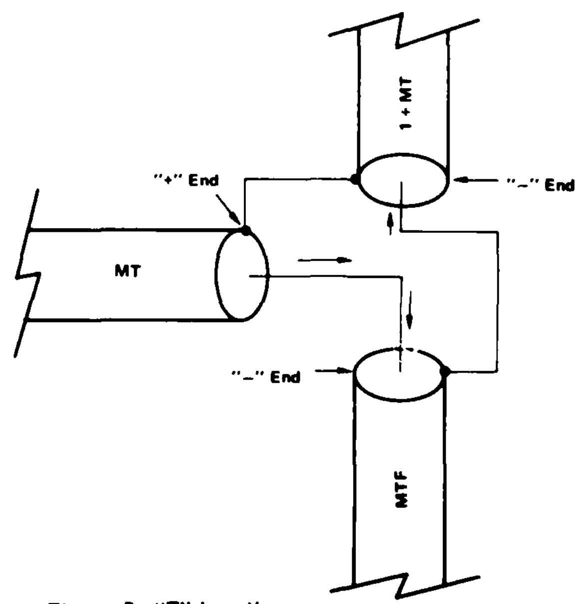


Figure 5. "T" junction.

3.4 *Switches*

In addition to the three types of junctions discussed so far, one further item is important in establishing the circuit topology: the switch. A switch can be designated between any consecutively numbered lines except at parallel or "T" junctions. A single "switch" between two lines actually has the effect of two switches, isolating both RG and RH from the lines during the time the switchs open, as shown in figure 6.

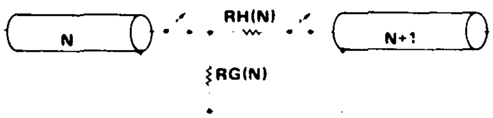


Figure 6. Resistive junction with switches.

Any of these switches can be designated a voltage-governed closing switch, a time-governed closing switch, a current-governed opening switch, or a time-governed opening switch. In fact, several of these designations could apply to a single switch. For example, the switch between lines 53 and 54 could be designated a switch that will be initially open, will close when the voltage between lines 53 and 54 reaches 9 MV, and will open again at 1800 ns. Since the switch between lines 53 and 54 is a voltage-governed switch, this might be designated in the array SWV, which contains a list of junction numbers with voltage-governed closing switches. So, one element of the array SWV must be set equal to 53, for example, SWV(5) = 53. Furthermore, since this switch closes at 9 MV, we must set VSH(5) equal to 9 MV. Since this is also a time-governed opening switch, some element of SWO is equated with 53, and the corresponding element of OPENT is set to 1800 ns. Table 1 summarizes the switch parameters.

TABLE 1. SWITCH PARAMETERS

Switch type	Governing parameter	Array designating position	Array of governing values
Closing	Voltage	SWV	VSH
Closing	Time	SWC	CLOSET
Opening	Current	SWI	ISH
Opening	Time	SWO	OPENT

As VSH indicates the maximum voltage for which the switch can remain open, ISH indicates the minimum current for which the switch can be sustained in the closed position. Should the user want ISH to indicate the maximum current a switch can sustain before opening (like a fuse), the logic can be adjusted in an easily recognized statement in the subroutine CALC in the source code.

As with the special junctions, the switch arrays are dimensioned for a maximum of nine of each type. The default value for an unused member of SWV, SWC, SWI, or SWO is 1. In the original version of the program, which assumed a switch following each element, it was necessary to specify that, for example, the switch following element 83 be open if MTF(2), for example, is 84. This would in effect eliminate the negative side of line 84 from any calculations involving the positive side of line 83. The new version TLINES takes care of such things automatically and no special switch need be specified. However, RG(83) would be removed from the circuit.

3.5 *Transit Time Considerations*

As mentioned in the introduction, all the transmission lines in a TLINES circuit have one length equal to the time step DT. Consequently, the user must simulate lines of differing lengths by

chains of differing numbers of transmission lines, taking into account that each line has the length DT. It is obvious from this that TLINES only accounts for lines of an integral multiple of DT. (The original version, through an interpolation procedure, permitted lines of any length equal to or greater than DT.) Considering that TLINES is dimensioned for 400 elements, for most purposes a real transmission line can be modelled with sufficient elements to give an accurate representation of its transit time.

3.6 *Initial Voltages*

Any of the lines (except for those with Z = 0 ohms) can be specified to be charged initially to a static voltage (see sect. 2). This sets up, in effect, the initial conditions. These voltage values are stored in the array VXP, which has one member for each line in the circuit. There is no need to put an open switch between lines that are charged initially to different voltages. Figure 7 gives a sample circuit illustrating concepts discussed to this point.

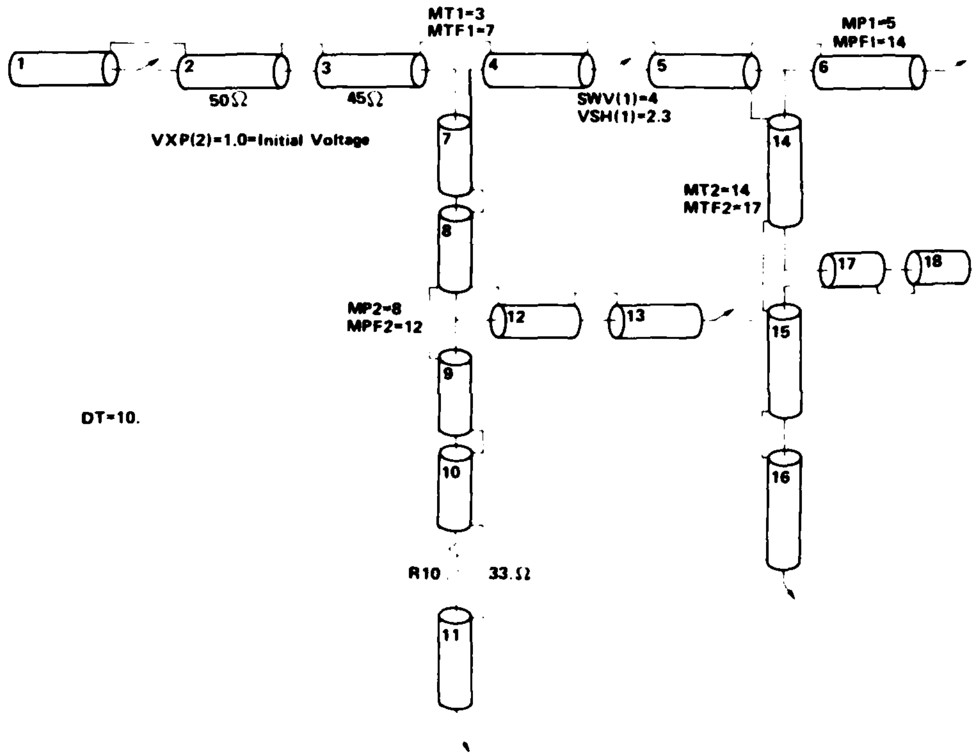


Figure 7. Sample layout of TLINES circuit.

3.7 *Terminations*

Terminations can be coded in one of the two ways shown in figure 8. In one instance, the resistor RH is used in conjunction with a zero-impedance transmission line; in the other instance, the resistor RG is used in conjunction with a very large impedance transmission line. RG cannot be used alone because an open switch at junction N would remove RG from the circuit.

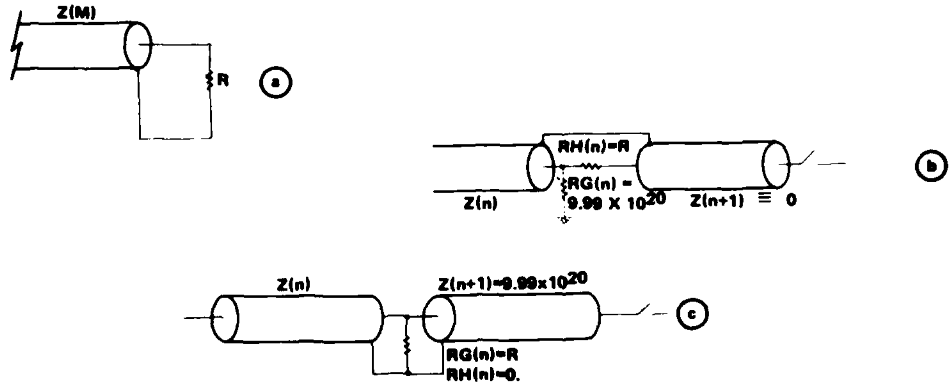


Figure 8. Terminations.

3.8 *Inductance and Capacitance*

As mentioned in section 2 transmission lines are characterized by an inductance and capacitance per unit length, with $Z = (L_0/C_0)^{1/2} = (L/C)^{1/2}$. In terms of the one-way transit time DT, L=Z*DT and C=DT/Z, where L and C are the values for the line of length DT. For large values of Z it is L that is most important; for small values of Z it is C that is most important. If the transmission line has a transit time DT short compared to the time interval for significant changes in circuit voltages, the line will react as a unit, behaving either as an inductor or a capacitor depending on its impedance and its configuration in the circuit. Some simple configurations are shown in figure 9, and the coding of the familiar R-L-C circuits is shown in figure 10. Appendix D gives a detailed study of the behavior of transmission lines as inductors and capacitors.

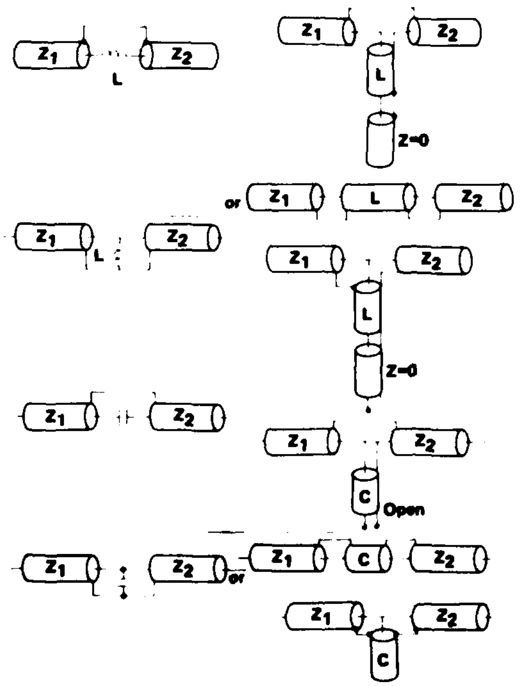


Figure 9. Using transmission lines to represent inductors and capacitors.

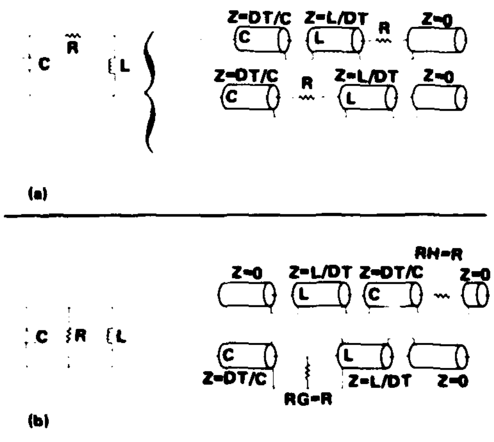


Figure 10. R-L-C circuits modelled with transmission lines.

3.9 *Loops of Transmission Lines*

Loops of transmission lines are possible with a little ingenuity. An example is shown in figure 11. It is important to keep in mind the conventions for "T" and parallel junctions when doing this. One might be concerned about the possibility of introducing ground loops through loops involving the "T" junction. However, the conventions for numbering transmission lines at the junctions (fig. 4 and 5) prohibit such things as modelling the Moebius-loop antenna.

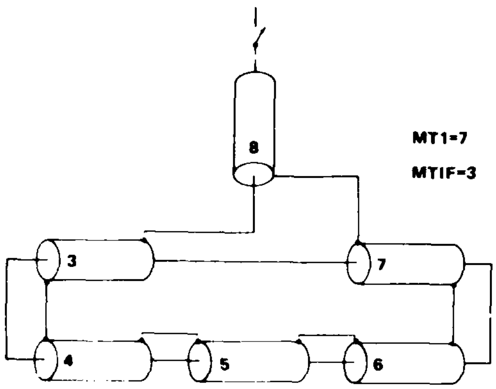


Figure 11. Loop of transmission lines.

4. RUNNING THE PROGRAM

If you have a good understanding of how the circuit is set up, running the program and doing the calculation is easy because the program prompts you for everything. In most cases the program will not permit you to make fatal errors. When important, the computer will indicate a format for data entry such as the following:

N MM --VALUE(REAL)-- under which you would type

3 5 69.65 for example. Or perhaps

5 23 14.

Note that the 5 and the 23 are right-justified under the heading MM, the value for N is typed directly under the heading N, and the real number is typed somewhere under --VALUE(REAL)--, using a decimal point.

The flowchart of the program is given in appendix E. The computer first wants to know whether the circuit parameters are new or old. If you answer that they are old, the computer will list the titles of the various circuits you have filed, request from you the number of the file in which you are interested, and then read the circuit parameters into memory.

If you indicate the parameters are new, the computer will proceed to ask for them one by one. Simply follow the instructions given at the terminal. If you enter a parameter incorrectly, you will be given a chance to correct it, if not immediately, then later. Some of the parameters (such as CAPM) have a direct bearing on what other parameters the computer will ask for or accept. For the Z's the computer prompts you for the value of each group of elements making up a string of elements having one impedance. The computer starts prompting at element 2; you enter the I.D. number of the last element in the string having the same value Z followed by that value. The com-

puter then prompts beginning with the next element, and so forth. If you err with one of these values, you will have to wait until later to correct it.

When entering the resistance RG to ground and the resistance RH between center conductors, it is not the value of each individual resistor in the circuit which is entered. Rather, it is the overall, effective value of RG or RH between two specified transmission lines that is entered. For example, consider that between transmission lines 10 through 20 each of the 10 junctions has an identical series resistance such that the overall series resistance between lines 10 and 20 is 50 ohms. Enter the numerical identifications of the two lines 10 and 20, and enter the value 50.0 (ohms). The computer then assigns the value 5.0 (ohms) to each of the 10 resistors RH(10) through RH(19). Similar steps are followed for the resistances RG. If the overall resistance to ground from element 10 up to element 20 is 0.2 ohms, the value to be entered is 0.2 (ohms). The computer will assign the value 2.0 (ohms) to each of the 10 resistors RG(10) through RG(19).

Once all the parameters are entered, the computer shows a menu of things you might like to do. The menu is as follows:

0...TO LIST THE PARAMETERS ON THE TERMINAL SCREEN
1...TO LIST THE PARAMETERS ON THE LINE PRINTER
2...TO ADJUST PARAMETERS
3...TO REVIEW THE PLOT LIST
4...TO FILE THE PARAMETERS
5...TO RUN THE CALCULATION
6...FOR PLOTS
7...TO EXIT PROGRAM
8...ADJUST THE PLOT INTERVAL
9...FOR A NEW COMMON GRAPH TITLE

4.1 *Listing*

If you enter 0 (or simply hit the return key) the parameters will be listed on the terminal screen. The computer will pause each time the screen fills. Once you have read or copied what is on the screen, hit the return key, and the computer will continue with the listing. Once the list has been completed, hit the return key, and the computer will take you back to the menu shown above. If you had entered 1, the same list of parameters would have been provided on the line printer.

4.2 *Parameter Adjustment*

If you enter 2, you will get your chance to correct your mistakes made entering the parameters, or, if the parameters were read from a file, you can modify them. You will be given another menu from which you identify the parameters you want to adjust. The circuit values referred to in this secondary menu are Z, RG, RH, and VXP, and these will be listed on a tertiary menu. Instructions are given with each menu on how to return (or "continue") to the next higher menu level, and this is simply to enter a blank or a zero by hitting the return key without entering a value. These instructions also indicate the format for entering the adjusted data.

4.3 *Plots Versus Time*

You can review and modify the plot list (by entering 3) before running the calculation. If no graphs are specified in the parameter file, the computer can do the calculation, but the output will be restricted to the snapshot plots of V, I, and P versus position.

The list of plots has room for up to nine entries. Each plot has a unique number K ranging from 1 through 9, and integer N specifying the physical quantity to be plotted, an integer S specifying whether the plot is for the positive or negative side of the line, and an integer MMM specifying the number of the transmission line of interest for the plot, the plot bounds, and an optional descriptive title such as "LOAD" or "SWITCH SIDE INTERMEDIATE STORE," or anything up to 32 characters. In addition to writing on the plot the descriptive user-supplied title for the particular plot and the title common to all plots, the computer identifies the physical quantity, such as "VOLTAGE AT RIGHT OF ELEMENT 13" or "CURRENT," for example, in the descriptive title. The quantity "POWER" is simply V*I at the left or right side of the specified element and is the energy per time entering (left side) or leaving (right side) that element. The "ENERGY" is the time integral of this power.

4.4 *Filing Parameters*

If you enter 4, the computer will list the titles that describe each circuit you have filed so you will know what is in each of the files. The computer will then ask in which file you would like to store the current set of parameters. Once you enter a number (1 through 9), whatever was in that file will be replaced with your current set of parameters. If, once you see the list of circuits, you decide you do not want to destroy any of them, enter 0 and the computer will return to the main menu without storing the parameters.

4.5 *Titles*

Also stored at the same time as the parameters is the common graph title. You can initially provide this title or alter it by entering 9. On the next line after entering 9, type the title. It is a good idea to say something in this title about the specific parameter variation for the particular calculation. This title heads all graphs and serves to document the calculation. This is also the title that describes the circuit that is stored in the various files, so it should say something about the overall circuit being analyzed.

4.6 *Plot Interval and Scaling*

During the course of the actual calculation, the program can plot on the terminal screen graphs of the voltage, current, and power distributions through the circuit. The time interval at which these plots are provided is adjusted by entering 8. Once 8 is entered, complete instructions are provided for making this adjustment. At this point in the program, you can also set the upper and lower limits of the graphs that will be plotted at the selected interval. There is no need to be overly worried about getting these limits right, because they can be changed during the course of the calculation. Similarly, the plot interval can be changed during the course of the program, as can the format of the graphs.

4.7 *Calculation and Snapshot Plots*

The actual calculation is started by entering 5 from the main menu. Once this is done a list of instructions will be shown on the screen. These instructions explain what character you should type to tell the computer to continue with the calculation after you have viewed (or copied) a snapshot plot. These are summarized here for reference:

0...(or simply return) To continue the calculation with the next set of plots in the same format as the present plots.

1...To adjust the plot interval or the upper and lower limits of the snapshot plots. The plots which immediately follow will have grid markings.

2...To end the calculation and return to the main menu without generating any time-dependent plots (which ordinarily would follow the completion of the calculation)

3...To show subsequent graphs without grid marks to save time.

4...To put the computer in an automatic rep mode where gridless graphs will be shown and the computer will continue with the calculations immediately after each graph is drawn. Once 4 has been entered you cannot enter anything else until the calculation has been completed. In the meantime you will be watching a "movie" of the wave progressions.

5...To change the total number of time steps the computer will be going through before leaving the calculation mode and going into the mode where time-dependent plots are shown. So if the calculation looks like it is getting interesting and you are about to run out of steps, you can keep it going by entering 5.

6...To return to plots with full grid markings.

After you have read this list of instructions, you are asked to signal the start of the actual calculation by entering

0...(or simply return) To begin the calculation at time = 0 (using the initial conditions established by the array VXP).

1...To begin the calculation where the last calculation stopped. If you enter 1, the program will once again step through the calculation the number of times indicated by NSTEPS and the final time-dependent plots will begin where the previous calculation finished.

The plots of V(x), I(x), and P(x)—referred to as "waves"—have an appearance similar to figure 1(a). The first set of plots to be shown represents the initial conditions at time = 0.0. Subsequent plots of waves show the results of the calculations which generate the waves leaving the junctions. These waves travel from the junction at which they originated to the junction at the opposite end of their respective transmission lines. As mentioned in section 2, and as can be seen in figure 1(a), no calculation is needed to figure out what happens as a wave traverses a transmission line from one end to the other, and there is no need to show the waves at as frequent intervals as in figure 1. Consequently, what is shown by the program is V(x), I(x), and P(x) at times exactly midway between calculations. It is at these times that the left-and right-going waves from opposite ends of a transmission line meet in the center of the line. For example, consider you have chosen a time step DT of 1.0 ns and a plot interval of 1.0 ns. The first waves plot will of course be the initial-condition plot. The second plot will give the results of the calculations for the first time step, showing the waves as they appear at 0.5 ns. The subsequent plots will be at 1.5, 2.5, 3.5 ns, etc. Had you chosen a plot interval of 50 ns, you would have seen plots at 0.0, 49.5, 99.5 ns, etc.

Each of the three plots—V(x), I(x), and P(x)—shows the voltage, current, or power distribution, respectively, through the transmission lines numbered 2 through CAPM. The left axis of each graph represents the position of the first junction (which is always open). Vertical lines through the graphs show the position of junctions at which the circuit is discontinuous. For example, if MTF(7) is line number 312, then a vertical line will be shown at the right side of element 311 to indicate that element 312 is not connected to element 311.

As already mentioned, once the computer has stepped through the calculation a number of times equal to NSTEPS, the time-dependent plots specified in the plot list will be shown. After viewing each graph, simply hit the return key to get the next graph. When the last graph has been shown, hitting the return key will put you back at the main menu.

To quit and leave the program elegantly without bombing, enter 7 when you are at the main menu. This is necessary if you would like to analyze a different circuit, since to bring a new circuit into memory you have to reenter the program.

4.8 *Reviewing the Plots Versus Time*

If, after having completed the calculation and viewing the plots of V(t), I(t), P(t), or E(t)—whatever you had previously specified, you would like to see them again, perhaps to refresh your memory or perhaps with a more appropriate set of bounds (which you would obtain by entering 3 from the main menu), simply enter 6 from the main menu, and the time-dependent plots you specified and that were generated by the calculation will be shown again.

5. A WORKED EXAMPLE

5.1 *Setting up the Circuit*

Consider the Blumlein circuit of figure 12. Imagine that the main switch has an inductance of 200 nH and an internal resistance of 2 ohms. The 10- and 15-ohm lines are initially charged to 5 MV, while both 35-ohm lines are initially uncharged. Separating the 35-ohm lines is a switch which is initially open but will close once 1 MV appears across the switch electrodes. Note that the greatest common divisor of all the transmission-line lengths is 5 ns. Therefore, we could choose a value of 5 ns for DT. However, imagine that the 200-nH switch is localized in a region much less than 5 ns in length. We would not want to represent that inductance with a transmission line as long as 5 ns, and would prefer having a transmission line less than 1-ns long represent the switch inductance. Therefore, we decide to try 0.5 ns for DT and, consequently, have a 0.5-ns line represent the switch inductance.

The TLINES format for the example circuit is shown in figure 13. The dummy line 1 is shown and, as always, it is not connected to line 2. The 15-ohm line, being 55 ns in length, is represented by the 110 lines numbered 2 through 111, while the 10-ohm line is modelled by 100 lines numbered 112 through 211. Similarly, the 5-ns and 10-ns lines are modelled by 10 and 20 lines, respectively.

Since it closes at t=0, the main switch need not be represented in the circuit. Line 213, which has an impedance of 0 ohms, serves as the path to ground through the closed switch. The switch resistance of 2 ohms is handled by RH(212). The 200-nH inductance is modelled by line 212, whose 400-ohm impedance comes from Z=L/DT.

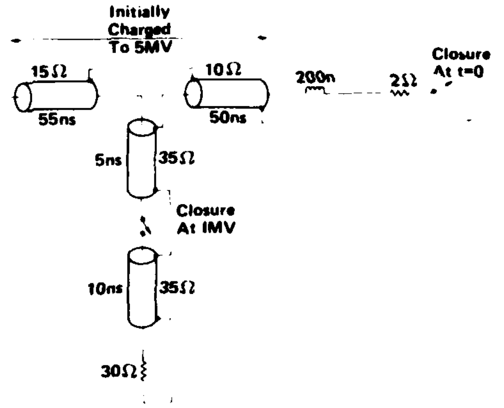


Figure 12. Circuit for demonstration Blumlein problem.

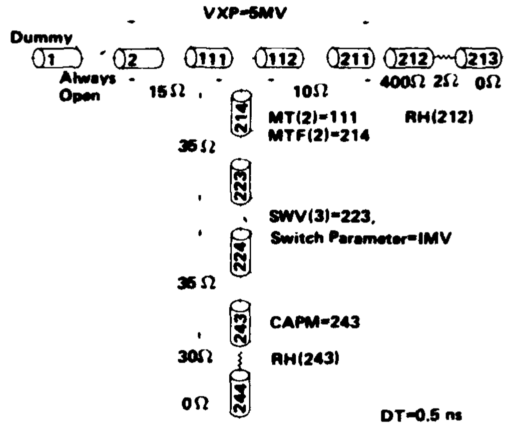


Figure 13. TLINES format of circuit in figure 12.

The "T" junction is taken care of if we specify that one member of the array MT(N) have the value 111, so we will arbitrarily choose MT(2) = 111. Then the corresponding member, N=2, of the array MTF(N) is given the value 214.

The second switch is at junction 223. Since this is a voltage-controlled closing switch, we must set one of the members of the array SWV equal to 223. So, in this example, we let SWV(3) = 223, and we correspondingly set its parameter (internally, VSH(3)) equal to 1 for the 1 MV closure. Consistent with the choice of MV units we set VXP(2) through VXP(211) equal to 5 to specify the initial charge.

The load appears at junction 243, so RH(243) = 30. The connection to ground of this resistor is handled by Z(244) = 0. Noting that 244 is the highest numbered element and that its impedance is 0, we can specify CAPM = 243 since line CAPM+1 always has an impedance of 0 ohms. (If we wanted element 244 to be other than 0 ohms, we would have set CAPM equal to 244 and would have put a switch at junction 244 with SWC or SWV having a governing parameter such that the switch would remain open for the entire duration of the calculation.)

5.2 *Running the Program*

In this section we explain the details of running the example outlined in section 5.1. What the computer displays is shown in **bold**; what the user is to type is shown in *italic*. To start the program on the PDP 11/60, type

RUN TLINES

The screen clears and you see

program TLINES
Sunday, 16 January 1983 (date of latest version)
circuit parameters are new (1) or old(2)?

In answer to this question, type 1 next to the question mark:

circuit parameters are new (1) or old(2)?*1*

then follow the 1 with the "return" key. (All entries are followed by "return".) The screen erases, and the program/user dialogue proceeds as follows:

enter the run title to here-- ---------------------------------!

Demonstration Blumlein Circuit

dt (real) = *.5*

max value for nsteps is 10000. nsteps (integer) = *1000* This can be changed later to a greater or lesser value.

max value for capm is 399. capm (integer) = *243.*

any voltage-, current-, or time-governed switches? (1-yes, 0-no): *1*

The screen erases and the following instructions are given:

under "t" enter

v-for voltage-governed closure
i-for current-governed opening
c-for time-governed closure
o-for time-governed opening

under "n" enter the id of the switch (1 thru 9)
under "mmm" enter the position (right-justified integer)
under "value" enter the governing voltage, current or time as a real

t n mmm --value---

V3 223 1.

In our example there is only one switch, so only one switch entry need be made. If there is more than one switch, make a list in any order following the data for each switch with "return." After the data for the last switch are typed and "return" is hit, hit "return" one more time to get the program out of the switch entry loop. The program then asks about junctions:

any junctions(1), none(0)--- *1*

the screen erases and instructions for junction entry are given:

enter the following as intergers, right-justified, under the appropriate heading. Type either "t" or "p" under s

sn msn msnf
T2 1 1 1 214

After completing the list of junctions, hit "return" once again as was done for the list of switches. The screen erases and the impedances are entered:

z(2) thru z(?) = ?	**mmm --value---**	
	1 1 1 15.	Lines 2 through 111 are 15 ohms.
z(112) thru z(?) = ?	**mmm --value---**	
	2 1 1 10.	If any mistakes are made in entering the data they can be fixed later.
z(212) thru z(?) = ?	**mmm --value---**	
	2 1 2 400.	
z(213) thru z(?) = ?	**mmm --value---**	
	2 1 3 0.	
z(214) thru z(?) = ?	**mmm --value---**	
	2 2 3 35.	
z(224) thru z(?) = ?	**mmm --value---**	
	2 4 3 35.	

Once all elements up to and including CAPM have been given their impedances, the screen erases and the program goes into the loop for series resistances.

rh rh rh rh rh

enter any non-zero series resistances
mmm is one element and nnn is another higher-numbered element
the resistance is the total series resistance between them
mmm= 0 to go on.

mmm n n n --resistance---
2 1 2 2 1 3 2.
2 4 3 2 4 4 30.

Once the list of series resistances is complete, once again hit an extra "return," and the program will go into the loop for entering the resistances RG.

rg rg rg rg rg

enter any non-infinite resistors to ground
mmm is one element and nnn is another higher-numbered element
the resistance is the over-all resistance to ground between the elements
mmm and nnn. If there is no resistor to ground, enter the value 0.

mmm nnn --resistance---

Since there are no finite resistances RG in the problem, simply hit "return," and the program enters the VXP loop:

vxp vxp vxp vxp vxp

enter the voltage of all elements not initially charged to zero.
vxp is the initial voltage on all elements
from mmm to nnn. mmm = 0 to go on.

mmm nnn vxp
2 211 5.

Once the list of initial voltages has been completed and an extra "return" has been made, the program lists the main menu:

in the i1 format, enter...

0...for parameter listing on terminal screen
1...for parameter listing on line printer
2...to adjust parameters
3...to review plot list
4...to file parameters
5...to run calculation and plot graphs
6...for plots only!
7...to exit program
8...to adjust plot interval or waves parameters
9...for a new common graph title (enter 9 (return),
then enter title, up to and including here)......................!
!

0

Since 0 was entered, the screen is cleared and the following list appears:

mm1	mm2	z	l	c	rh	rg	vxp
demonstration blumlein circuit							
1	1	1.000e+00	5.000e−01	5.000e−01	0.000e−01	9.999e+20	0.000e−01
2	111	1.500e+01	7.500e+00	3.333e−02	0.000e−01	9.999e+20	5.000e+00
112	211	1.000e+01	5.000e+00	5.000e−02	0.000e−01	9.999e+20	5.000e+00
212	212	4.000e+02	2.000e+02	1.250e−03	2.000e+00	9.999e+20	0.000e−01
213	213	0.000e−01	0.000e−01	5.000e+19	0.000e−01	9.999e+20	0.000e−01
214	242	3.500e+01	1.750e+01	1.429e−02	0.000e−01	9.999e+20	0.000e−01
243	243	3.500e+01	1.750e+01	1.429e−02	3.000e+01	9.999e+20	0.000e−01

On any given line in the above list, Z, RH, RG, and VXP are the same from line MM1 through line MM2. Also listed for reference are L and C for each line of length DT: L = Z*DT, C = DT/Z. Note that for the case where Z = 0, C is given as 5×10^{19}, an arbitrary value. Once you have read over this list of parameters, hit "return" and the parameter listing will continue:

	junctions				voltage-gov closing		current-gov opening		timed closing		timed opening	
n	mt	mtf	mp	mpf	swv	voltage	swi	current	swc	time	swo	time
1	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
2	111	214	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
3	1	1	1	1	223	1.00e+00	0	0.00e−01	0	9.99e+20	0	0.00e−01
4	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
5	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
6	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
7	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
8	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01
9	1	1	1	1	0	0.00e−01	0	0.00e−01	0	9.99e+20	0	0.00e−01

capm = 243 dt = 5.00e−01 nsteps = 1000

In the list shown above, there is one column for each of the junction and switch arrays. The index (1 through 9) is given in the first column under "N." After viewing this list hit "return," and the program returns to a display of the main menu.

For a permanent listing of the parameters other than a hard copy of the actual terminal screen, we would enter 1 from the main menu. Since the parameters are satisfactory, there is no need to adjust them, which could have been done by entering 2. To specify what plots are desired as output, enter 3, and the program gives instructions:

enters s=1 for left side, or s=2 for right side
n = 1 ... i
n = 2 ... v
n = 3 ... p
n = 4 ... e
k is the plot number and mmm is the element number

ksn mmm min(real) max(real) title---title---title---title---
end of plot-parameter list

when satisfied with plot list, k = 0
to delete a plot, give k and let s = 9 or 0
to add a plot, use the following format

ksn mmm min(real) max(real) title---title---title---title---
```
122 2 4 3 -15.      15.       LOAD
221 2 4 3 -.5       .5        LOAD
323 2 4 3  0.       .0 75     LOAD
424 2 4 3  0.       110.      LOAD
```

Since this is a new circuit, there existed no prior information on the parameters of output plots. Consequently, the message "end of plot-parameter list" follows the non-existing list of what would have been parameters for output plots. The next time 3 is entered from the main menu, the parameters entered above will be shown for reference. The min and max values entered above are guesses, and there is no need to be overly concerned with them because, once generated, a graph can always be redrawn with corrected scaling. There is, however, some reasoning in the values entered as above. The values for the voltage plot (k=1) are purely guesses. But noting that the load is 30 ohms, the min and max for the current plot (k=2) were chosen to be consistent using V/R=I. The power (k=3), which is V^2/R for a resistor by itself, can never be less than 0, and, to be consistent with the voltage guess would have a maximum of 7.5 terawatts. The value .075 was deliberately entered as a mistake here for illustrative purposes. The energy delivered to a resistor also has a minimum of 0. The maximum chosen for the energy (K=4) plot is based on the total energy stored in the transmission lines at t=0 using $W=\frac{1}{2}CV^2$, where C comes from C=DT/Z for each of the initially charged lines. (C for each line is shown in the listing of the circuit parameters.)

After the list of plot parameters has been completed, hit an extra "return" as indicated by the instruction to enter K = 0. (With FORTRAN programs, entering a "blank" by simply hitting "return" is understood by the program as the quantity 0 for numerical input.) This entry returns you to the main menu.

Before actually doing the calculation, you would want to specify the time interval for viewing the snapshot plots of V, I, and P. (If nothing is done about this, the default is not to view these plots at all.) Entering 8 from the main menu permits you to view these plots:

8

the plot interval is -1.00000 in time units
if negative, no plots vs position
to adjust, enter value; if ok, hit return
-----value-----
10.

enter new values for subroutine waves plotting parameters

n = 1	n = 2	n = 3	n = 4	n = 5	n = 6
vltmin	vltmax	curmin	curmax	powmin	powmax
−0.200e+1	0.200e+01	−0.200e+01	0.200e+01	−0.200e+01	0.200e+01

n --value---

1 −15.
2 15.
3 −5.
4 5.
5 −.075
6 .075

Although there is no reason to base these max and min values on the max and min values chosen for the time-dependent plots at the load position, we did just that for lack of anything better to do. The same very-wrong value for the power (0.075 TW) is used here for illustration. Note that a negative minimum is chosen for power, since in a transmission line power can flow in both directions. Since DT is 0.5 ns, specifying 10 ns for the plot interval will generate a plot every 20 time steps. As usual, an *extra "return"* when finished with the above data returns the program to the position of the calling (in this case, main) menu.

At this point we could run the calculation. However, since we have spent a little time entering these data into the computer, it would be nice to save them permanently just in case something goes wrong. To do this enter *4*:

4
0= *...*** do not file parameters ***...*****
1= hifx simulation for experiments of fall 1982
2= dragon
3=test number 3
4=test 5 -- big long loop -- h 1 jul 82
5=test 4 -- t's -- u 29 jun 82
6=test 6 -- aurora model (version 3 gah book 7012, pg 5) -- w 30 jun 82
7=switch test. z=1. vxp(2−21)=1. rh(32)=1. 31=typical sw position.
8=simple aurora model: no sw l, constant z's all over, minor "t" removed.
9=rogowski coil-integrator, july 21, 1982, marc litz

enter the file number of the data file: *3*

With this entry, the data previously stored in file 3 are replaced with the new data, and the program returns to the main menu.

We are now ready for the calculation:

5

options available while running waves (enter as an integer after each graph is drawn)

0...continue program
1...adjust plot interval or waves parameters
2...end all calculations and return to main menu
3...draw the traces without the grid marks and boxes
4...draw the trace only, and do not pause for any new options
5...change nsteps
6...set a normal plot

the option remains in effect until another option is chosen

****

0 = begin calculation at time = 0
1 = continue calculation

enter choice: *0*

A plot of the initial conditions is now drawn. When you finish viewing this plot, hit "return," and the first of the snapshot plots is drawn as in figure 14. We immediately see our error in the amplitude chosen for plotting power. So, instead of hitting "return" we hit 1, followed by "return" to adjust the waves parameters.

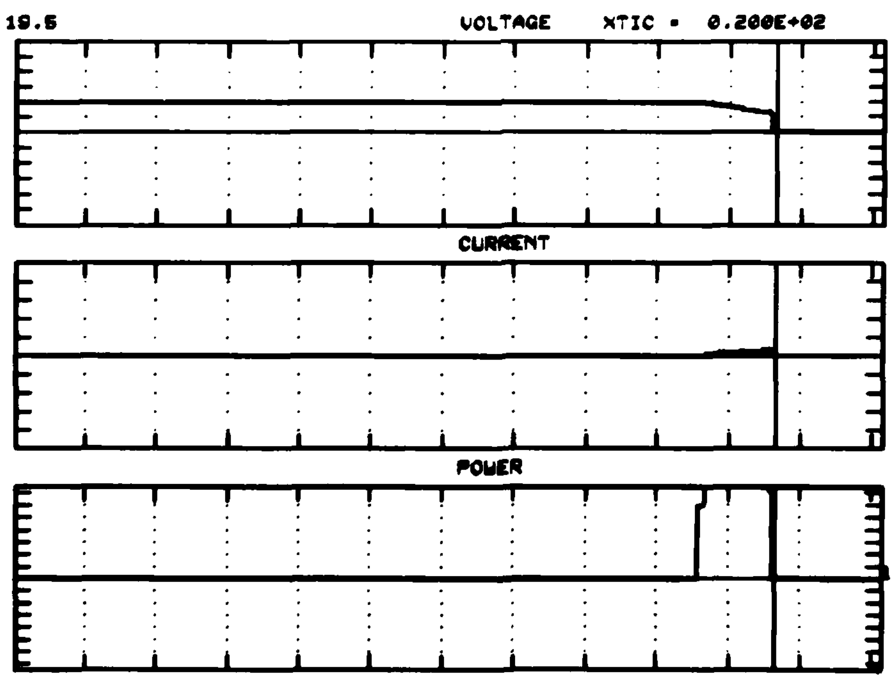


Figure 14. First snapshot of propagating waves.

1 (at right of power graph)

After we reenter the mins and maxes that need adjustment and hit an extra "return," our snapshot plots are redrawn as shown in figure 15. Note that we have corrected the current for a min of −0.5 and a max of 0.5 and the power for a min of −0.75 and a max of 0.75.

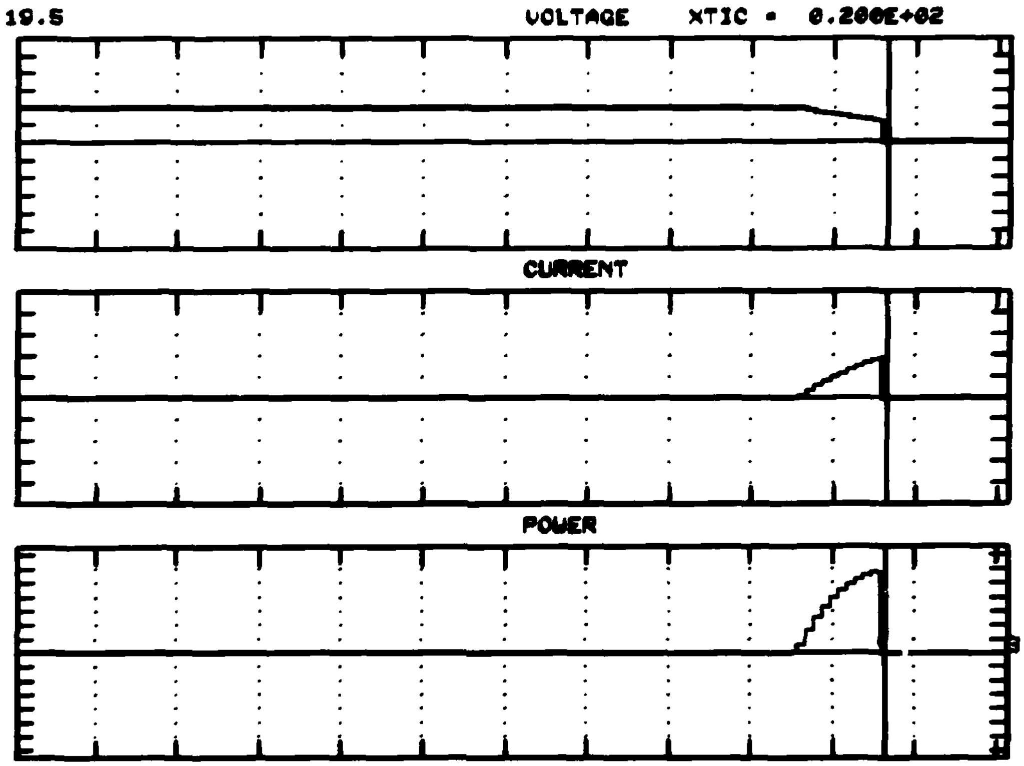


Figure 15. First snapshot with corrected scaling.

Liking what we see, we choose to continue with the calculation, but without the burden of having to wait for the grid markers to be drawn. So we enter a *3* at the right of the power plot:

3

and the next time step is illustrated without grid markings, as in figure 16. Note that in these graphs the x-axis is circuit position. A vertical marker indicates where in the enumeration of circuit position there is a discontinuity due to a junction. In our example, this discontinuity is between elements 213 and 214.

If you tire of viewing these snapshot plots, enter *1* at the right of the power plot. Then enter a negative number for the plot interval and hit a "return" after the plotting parameter section to continue the calculation without the snapshots.

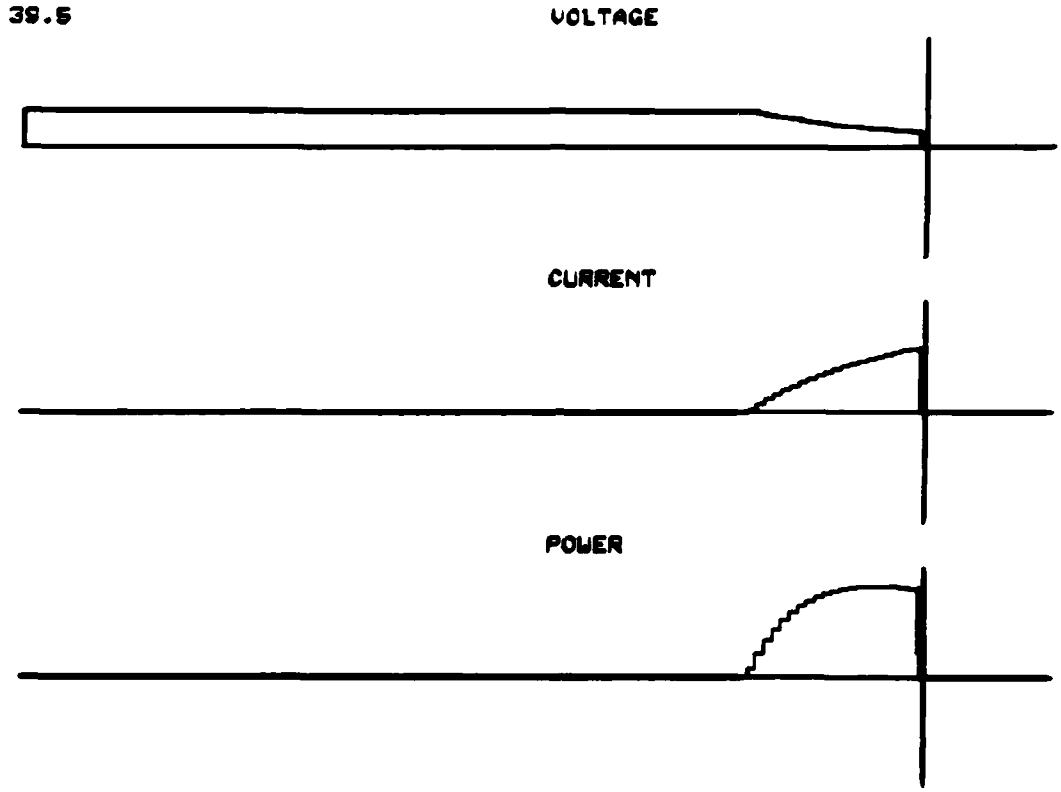


Figure 16. Second snapshot without grid markings.

To let you know of its progress, the program will give the time step number every 50 steps:

time step = 150
time step = 200
time step = 250

etc., until the calculation is completed. Once the calculation has been completed, the program will give the message

data are being transferred from yarray.dat to newy.dat

4 blocks with 1000 lines each involved

please be patient

1 of 4 blocks completed
2 of 4 blocks completed
3 of 4 blocks completed
4 of 4 blocks completed

Now that the data have been reorganized for plotting, the first of the time-dependent plots is drawn as shown in figure 17. Note that the x-axis is labeled in time steps, while the y-axis is labeled in physical units. After viewing each graph, hit "return." After the last graph has been viewed, the program returns to the main menu. Since we would like to correct the scaling on the power plot, enter

3

and our list of plot parameters will be shown. Since it is only the power plot (K=3) that needs adjustment, simply reenter the data for the plot only. Once you are back at the main menu, enter

6

to view the time-dependent plots once again with the adjusted scaling.

Finally, back at the main menu, enter

7

to terminate the program.

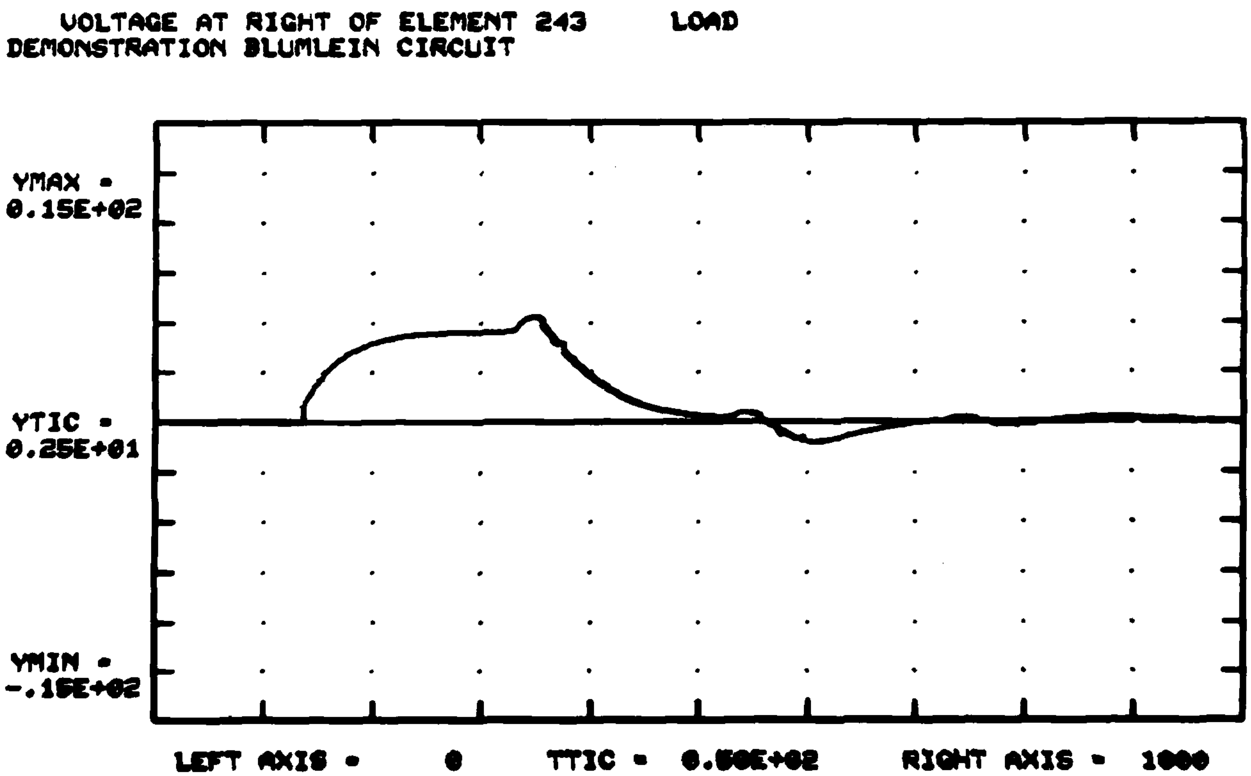


Figure 17. First time-dependent plot.

Appendix A.—Relevant Files

The files relevant to the installation of TLINES on the Aurora PDP-11/60 computer are the following:

TLINES.FTN
TLINES.OBJ
TLINES.CMD
TLINES.TSK
PROJCT.DAT
1.DAT
2.DAT
3.DAT
4.DAT
5.DAT
6.DAT
7.DAT
8.DAT
9.DAT

TLINES.FTN is the FORTRAN source code. TLINES.OBJ is the object module generated during the compilation of TLINES.FTN and is necessary only to generate the load module TLINES.TSK. The load module is generated with the help of the command file TLINES.CMD, which contains information on the assignments of the logical unit numbers and on the files containing the graphics subroutines necessary for plotting at the terminal. TLINES.CMD is listed below:

```
TLINES/CP=TLINES,DM1: [100,100]TCS/LB
/
UNITS=7
ASG=DM0:1
ASG=TI:5
ASG=TI:6
ASG=LP:7
ACTFIL=3
PRI=90
//
```

PROJCT.DAT is a data file containing the list of titles for each of the nine circuits that could conceivably be on file. These nine circuits are stored in the files 1.DAT through 9.DAT.

The only file absolutely necessary to run TLINES is TLINES.TSK. However, if you want to do anything concerning the permanent storage of one or more sets of circuit parameters, you will also need PROJCT.DAT, since PROJCT.DAT is read by the program before reading into memory a previously stored circuit or before filing the circuit currently in use. When you file your circuit parameters you will be generating one of the files n.DAT, and you will be deleting any file currently existing with the same name. Of course, to analyze an old circuit, you will previously have had to generate one of the files n.DAT using TLINES.

Appendix B.—Derivation of Circuit Equations

B-1. THE "T" JUNCTION

The wiring of the "T" junction was shown in figure 5, body of report. In the calculation of the equations for this junction, we consider the static voltages in the three lines and the waves arriving at the junctions to be known. These values include V_0(MTn), V_0(1+MTn) V_0(MTFn), VMXM(1+MTn), VMXM(MTFn), and VPXP(MTn). The values VMXM(MTn), VPXM(1+MTn), and VPXM(MTFn)of the waves leaving the junction are to be solved for. (Refer to section 2, body of report, for the defintions of the wave variables.) There are two conditions which must be satisfied. First, *the voltages must add properly:*

$$\begin{aligned}
&V_0(\mathrm{MTn}) + \mathrm{VPXP(MTn)} + \mathrm{VMXP(MTn)} = \\
&\qquad V_0(1+\mathrm{MTn}) + \mathrm{VMXM}(1+\mathrm{MTn}) + \mathrm{VPXM}(1+\mathrm{MTn}) + \\
&\qquad V_0(\mathrm{MTFn}) + \mathrm{VMXM(MTFn)} + \mathrm{VPXM(MTFn)}\ .
\end{aligned} \tag{B-1}$$

Note that the voltages are defined as the potential of the inner conductor minus the potential of the outer conductor. Secondly, the current out of line MTn must equal the current into MTFn, which in turn must equal the current into line 1+MTn:

$$\begin{aligned}
\mathrm{I} &= [\mathrm{VPXP(MTn)} - \mathrm{VMXP(MTn)}]/\mathrm{Z(MTn)} \\
&= [\mathrm{VPXM(1{+}MTN)} - \mathrm{VMXM(1{+}MTn)}]/\mathrm{Z(1{+}MTn)} \\
&= [\mathrm{VPXM(MTFn)} - \mathrm{VMXM(MTFn)}]/\mathrm{Z(MTFn)}\ .
\end{aligned} \tag{B-2}$$

Using equations (B-2), the unknowns *in equation (B-1) are simply replaced in terms of the single* unknown I and the known waves approaching the junction. The solution for I is

$$\mathrm{I} = \frac{[V_0\,(\mathrm{MTn}) - V_0(1+\mathrm{MTn}) - V_0(\mathrm{MTFn})] + 2[\mathrm{VPXP(MTn)} - \mathrm{VMXM(1{+}MTn)} - \mathrm{VMXM(MTFn)}]}{\mathrm{Z(MTn)} + \mathrm{Z(1{+}MTn)} + \mathrm{Z(MTFn)}}\ . \tag{B-3}$$

Each of the three unknown waves leaving the junction is then found by using in each of equations (B-2) the current as given *in* equation (B-3).

B-2. THE PARALLEL JUNCTION

The second of the three junctions to be considered is the *parallel junction, as was shown in* figure 4, *body of report*. In this situation it is the voltages which are equal and the currents which must add, as in the following expressions:

$$\begin{aligned}
V &= V_0(\mathrm{MPn}) + \mathrm{VPXP(MPn)} + \mathrm{VMXP(MPn)}\ , \\
&= V_0(1+\mathrm{MPn}) + \mathrm{VPXM(1{+}MPn)} + \mathrm{VMXM(1{+}MPn)}\ , \\
&= V_0(\mathrm{MPFn}) + \mathrm{VPXM(MPFn)} + \mathrm{VMXM(MPFn)}\ , \text{ and}
\end{aligned} \tag{B-4}$$

$$\mathrm{I(MPn)} = \mathrm{I(1{+}MPn)} + \mathrm{I(MPFn)} \tag{B-5}$$

The individual current terms in equation (B-5) are written similarly to the terms in equation (B-2) (of course substituting the index MPn for MTn and substituting the index MPFn for MTFn). For this calculation it is convenient to use the individual voltage expressions of equations (B-4) to replace the unknown waves in the expanded form of equation (B-5) with the single unknown V. Solving for V we obtain equation (B-6):

$$V = \frac{\dfrac{V_o(MPn)+2VPXP(MPn)}{Z(MPn)} + \dfrac{V_o(1+MPn)+2VMXM(1+MPn)}{Z(1+MPn)} + \dfrac{V_o(MPFn)+2VMXM(MPFn)}{Z(MPFn)}}{Z^{-1}(MPn) + Z^{-1}(1+MPn) + Z^{-1}(MPFn)} \quad . \tag{B-6}$$

Each of the unknown voltage waves leaving the junction is then obtained by using the expression for V in each of the equations (B-4).

B-3. THE RESISTIVE JUNCTION

Figure 6 shows the arrangement of the resistive junction. We will assume the switches (remember that both work together as a unit) are closed. Similar to the previous analyses, the voltages at the ends of the two transmission lines are

$$\begin{aligned} V(N) &= V_o(N) + VPXP(N) + VMXP(N), \\ V(N+1) &= V_o(N+1) + VPXM(N+1) + VMXM(N+1) \quad , \end{aligned} \tag{B-7}$$

and each current in its respective transmission line is given by

$$\begin{aligned} Z(N)I(N) &= VPXP(N) - VMXP(N), \\ Z(N+1)I(N+1) &= VPXM(N+1) - VMXM(N+1) \quad . \end{aligned} \tag{B-8}$$

The voltages V(N) and V(N+1) are related through

$$V(N) = V(N+1) + I(N+1)RH(N) \quad , \tag{B-9}$$

while the currents are related through

$$V(N) = [I(N) - I(N+1)]\, RG(N) \quad . \tag{B-10}$$

Equations (B-7), (B-8), (B-9), and (B-10) incorporate six independent equations which can be solved simultaneously for the six unknowns: V(N), V(N+1), VMXP(N), VPXM(N+1), I(N), and I(N+1). Making use of the substitutions

$$\begin{aligned} V1 &= V_o(N) + 2VPXP(N), \\ V2 &= V_o(N+1) + 2VMXM(N+1), \text{ and} \\ D &= Z(N) + [RH(N) + Z(N+1)]\,[1 + Z(N)/RG(N)], \end{aligned} \tag{B-11}$$

the two currents have the solutions

$$\begin{aligned} I(N) &= [(\frac{RH(N) + Z(N+1)}{RG(N)} + 1) * V1 - V2]/D \quad , \\ I(N+1) &= (V1 - (\frac{Z(N)}{RG(N)} + 1) * V2]/D \quad . \end{aligned} \tag{B-12}$$

The waves leaving the junction VMXP(N) and VPXM(N+1), which are of more immediate interest in the program, are found by substituting equations (B-12) into equations (B-8).

If the switch is open, no calculation is done. Instead, a very simple substitution is made: VMXP(N) = VPXP(N), and VPXM(N+1) = VMXM(N+1). These substitutions follow from the above results if RG(N), and RH(N) are each allowed to approach infinity. But without going through all that trouble it is sufficient to note that the waves reflected from open-ended transmission lines are equal in amplitude to the waves arriving at the open end.

Appendix C.—Listing of Subtroutine CALC

```
C
C    CALC ('CALCULATION') DOES THE CALCULATION, ONE TIME
C    STEP PER CALL.
C
        SUBROUTINE CALC (MMAX)
        INTEGER*2 ICONS(9),MS(9)
        LOGICAL*1 RHINF(400)
        DIMENSION HEADER(8), MT(9), MTF(9), MP(9), MPF(9), PROJCT(18)
        DIMENSION TITLE(9,8), YMIN(9), YMAX(9)
        INTEGER STEP,CAPM,TDIMEN,SWV(9),SWI(9),SWC(9),SWO(9)
        REAL RG(400), RH(400), Z(400), VXP(400)
        REAL VMXM(400), VPXP(400), VMXP(400), VPXM(400)
        REAL ISH(9), VSH(9), CLOSET(9), OPENT(9)
        COMMON/BK/VPXP,VMXM,VPXM,VMXP,TIME,RG,RH,VSH,ISH,VXP,Z,
       1 MT,MTF,MP,MPF,CLOSET,OPENT,SWV,SWI,SWC,SWO
        COMMON/PLOT/PROJCT,HEADER,YMIN,YMAX
        COMMON/DT/DT
        COMMON STEP,CAPM,RHINF
        COMMON/DATA/ICONS,TITLE,PLTINT,MS,BLANK,TDIMEN
        TIME = DT * (STEP - 1)
C
C       THE SWITCH IS TURNED ON IF THE VOLTAGE IS LARGE ENOUGH.
C       (THE SWITCH IS OPEN IF RHINF(M) IS .TRUE. AND
C                    CLOSED IF RHINF(M) IS .FALSE.)
C
        DO 7 M = 2, CAPM
        IF (RHINF(M)) GO TO 6
        DO 16 K=1,9
        IF (M .NE. SWI(K)) GO TO 16
        IF (Z(M) .EQ. 0) GO TO 19
        CURENT = (VPXP(M) - VMXP(M))/Z(M)
        GO TO 18
     19 IF (Z(M+1) .EQ. 0) GO TO 16
        CURENT = (VPXM(M+1) - VMXM(M+1))/Z(M+1)
     18 IF (ABS(CURENT) .LE. ABS(ISH(K))) RHINF(M)=.TRUE.
     16 IF ((M .EQ. SWO(K)) .AND. (TIME .GE. OPENT(K))) RHINF(M)=.TRUE.
        GO TO 7
      6 DO 17 K = 1, 9
        IF (M .NE. SWV(K)) GO TO 17
        SWVOLT=VXP(M)+VPXP(M)+VMXP(M)-VXP(M+1)-VPXM(M+1)-VMXM(M+1)
        IF (((VSH(K) .GE. 0.) .AND. (SWVOLT .GE. VSH(K))) .OR.
       1     ((VSH(K) .LT. 0.) .AND. (SWVOLT .LE. VSH(K))))RHINF(M)=.FALSE.
C
C     THE LOGIC OF THE ABOVE TWO LINES PERMITS POLARITY-DEPENDENT SWITCHING.
C     HOWEVER, WITH THIS LOGIC THE USER MUST KEEP IN MIND HOW POLARITY OF
C     THE SWITCH VOLTAGE 'SWVOLT' IS DEFINED.  FOR A SIMPLER USAGE OF THE
C     PROGRAM, THE FOLLOWING LINE IS SUGGESTED AS A SUBSTITUTE FOR THE
C     TWO LINES ABOVE...
C
C       IF (ABS(SWVOLT) .GE. VSH(K)) RHINF(M)=.FALSE.
C
     17 IF ((M .EQ. SWC(K) .AND. TIME .GE. CLOSET(K))) RHINF(M)=.FALSE.
      7 CONTINUE
C
C       THE TRAVELLING VOLTAGE WAVES COMING INTO JUNCTIONS BETWEEN
C       TRANSMISSION LINE SEGMENTS ARE CALCULATED IN TERMS OF THE
```

```
C     OUTGOING WAVES AT THE OPPOSITE ENDS OF THE SEGMENTS.
C
      DO 1 M = 1, CAPM
      VPXP(M) = VPXM(M)
    1 VMXM(M) = VMXP(M)
C
C     THE TRAVELLING VOLTAGE WAVES GOING OUT FROM THE JUNCTIONS ARE
C     CALCULATED.
C
      VPXM(2) = VMXM(2)
      DO 3 M = 2, CAPM
      DO 5 K = 1, 9
      IF (M .EQ. MT(K)) GO TO 999
    5 IF (M .EQ. MP(K)) GO TO 107
      IF (.NOT. RHINF(M)) GO TO 998
      VMXP(M) = VPXP(M)
      DO 997 K = 1, 9
      IF (M+1 .EQ. MTF(K)) GO TO 3
  997 IF (M+1 .EQ. MPF(K)) GO TO 3
      VPXM(M+1) = VMXM(M+1)
      GO TO 3
  998 DENOM = Z(M) + (RH(M) + Z(M+1))*(1. + Z(M)/RG(M))
      V1 = VXP(M) + 2. * VPXP(M)
      V2 = VXP(M+1) + 2. * VMXM(M+1)
      VMXP(M) = VPXP(M) - Z(M) * ((((RH(M) + Z(M+1)) / RG(M) + 1.)
     1          * V1 - V2) / DENOM)
      VPXM(M+1) = VMXM(M+1) + Z(M+1) * ((V1 - (Z(M) / RG(M) + 1.)
     1          * V2) / DENOM)
      GO TO 3
  999 MT1F = MTF(K)
      CURENT = (VXP(M) - VXP(M+1) - VXP(MT1F) + 2. * VPXP(M) -
     1 2. * VMXM(M+1) - 2. * VMXM(MT1F)) / (Z(MT1F) + Z(M) + Z(M+1))
      VMXP(M) = VPXP(M) - Z(M) * CURENT
      VPXM(M+1) = VMXM(M+1) + Z(M+1) * CURENT
      VPXM(MT1F) = VMXM(MT1F) + Z(MT1F) * CURENT
      GO TO 3
  107 MP1F = MPF(K)
      V = ((2. * VPXP(M) + VXP(M)) / Z(M) + (2. * VMXM(M+1) + VXP(M+1))
     1 / Z(M+1) + (2. * VMXM(MP1F) + VXP(MP1F)) / Z(MP1F))
     2 / (1./Z(M) + 1./Z(M+1) + 1./Z(MP1F))
      VMXP(M) = V - VXP(M) - VPXP(M)
      VPXM(M+1) = V - VXP(M+1) - VMXM(M+1)
      VPXM(MP1F) = V - VXP(MP1F) - VMXM(MP1F)
    3 CONTINUE
      RETURN
      END
C**************************************************************************
```

Appendix D.—Theoretical Look at Transmission Lines as Inductors and Capacitors in TLINES

Our goal in this section is to show how the algebra of waves in transmission lines leads to the formulas V = LI and V = Q/C, which are important in transient analyses of circuits containing inductors and capacitors. Consider a transmission line of impedance Z and one-way transit time DT. This line is shown in figure D-1, in which the waves are pictured at a time $t = t_1 + 0.1$ DT, where t_1 is the time of one of the steps in the calculation.

D-1. INDUCTORS

The voltage drop V across the center conductor of the transmission line in going from one end of the line to the other is given by

$$V = V_{left} - V_{right} = VPXM(t_1) + VMXM(t_1) - VPXP(t_1) - VMXP(t_1) \quad , \qquad \text{(D-1)}$$

which is valid and has the same numerical quantity for all time t from t_1 to t_1 + DT. At time t_1, the current throughout the transmission line is given by $I(t_1)$:

$$I(t_1) = [VPXP(t_1) - VMXM(t_1)]/Z \quad , \qquad \text{(D-2)}$$

and at the end of the interval ($t=t_1+Dt=t_2$) the current $I(T_2)$ is given by

$$I(t_2) = [VPXM(t_1) - VMXP(t_1)]/Z \quad . \qquad \text{(D-3)}$$

Note that the current values $I(t_1)$ and $I(t_2)$ as expressed in equations (D-1) and (D-2) give the current within the transmission line and not at the junctions (refer to fig. D-1). Continuously and linearly over the interval from t_1 to t_2 the average current in the transmission line changes from $I(t_1)$ to $I(t_2)$. *Consequently, it is reasonable to think in terms of the derivative of the average current in the* line throughout the interval t_1 to t_2, and this derivative is give by

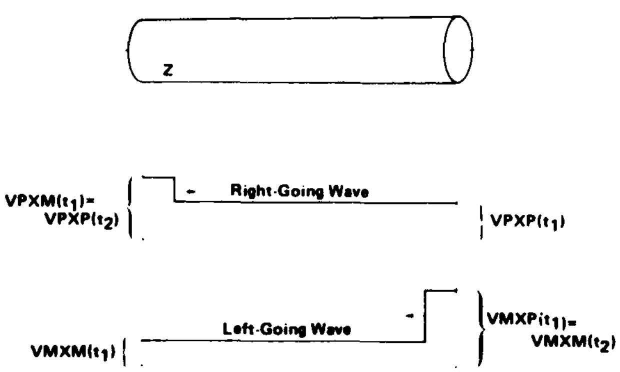


Figure D-1. Waves in transmission line at time $t = t_1 + .1$ DT.

Waves In A Transmission Line At Time $t=t_1 + 0.1$ DT.

$$\dot{I} = Z^{-1} [VPXM(t_1) - VMXP(t_1) - VPXP(t_1) + VMXM(t_1)]/DT \quad . \qquad \text{(D-4)}$$

Note that the bracketed terms in equation (D-4) are identical to the terms on the right side of equation (D-1). Therefore, we have

$$DT\, Z\, \dot{I} = V, \qquad \text{(D-5)}$$

and recalling that DT Z = L, we can state that

$$L\dot{I} = V. \tag{D-6}$$

D-2. CAPACITORS

Throughout the interval t_1 to t_2, the rate at which charge is accumulated in the line $\dot{Q}$ is given by the current entering the line at left minus the current leaving the line at the right:

$$\dot{Q} = [VPXM(t_1) - VMXM(t_1)]/Z - [VPXP(t_1) - VMXP(t_1)]/Z \quad ,$$

or (D-7)

$$Z\,\dot{Q} = VPXM(t_1) - VMXM(t_1) - VPXP(t_1) + VMXP(t_1) \quad .$$

At the beginning of the interval $t = t_1$, the voltage in the line is given by $V(t_1)$:

$$V(t_1) = VPXP(t_1) + VMXM(t_1) + VXP, \tag{D-8}$$

and at the end of the interval the voltage throughout the line is given by

$$V(t_2) = VPXM(t_1) + VMXP(t_1) + VXP. \tag{D-9}$$

Between times t_1 and t_2 the voltage throughout the line is not constant, but its average is changing linearly such that

$$\dot{V} = [VPXM(t_1) + VMXP(t_1) - VPXP(t_1) - VMXM(t_1)]/DT \quad . \tag{D-10}$$

Noting that the terms in the brackets of equation (D-10) equal the right side of (D-7), we can state that

$$Z\,\dot{Q} = \dot{V}\,DT, \tag{D-11}$$

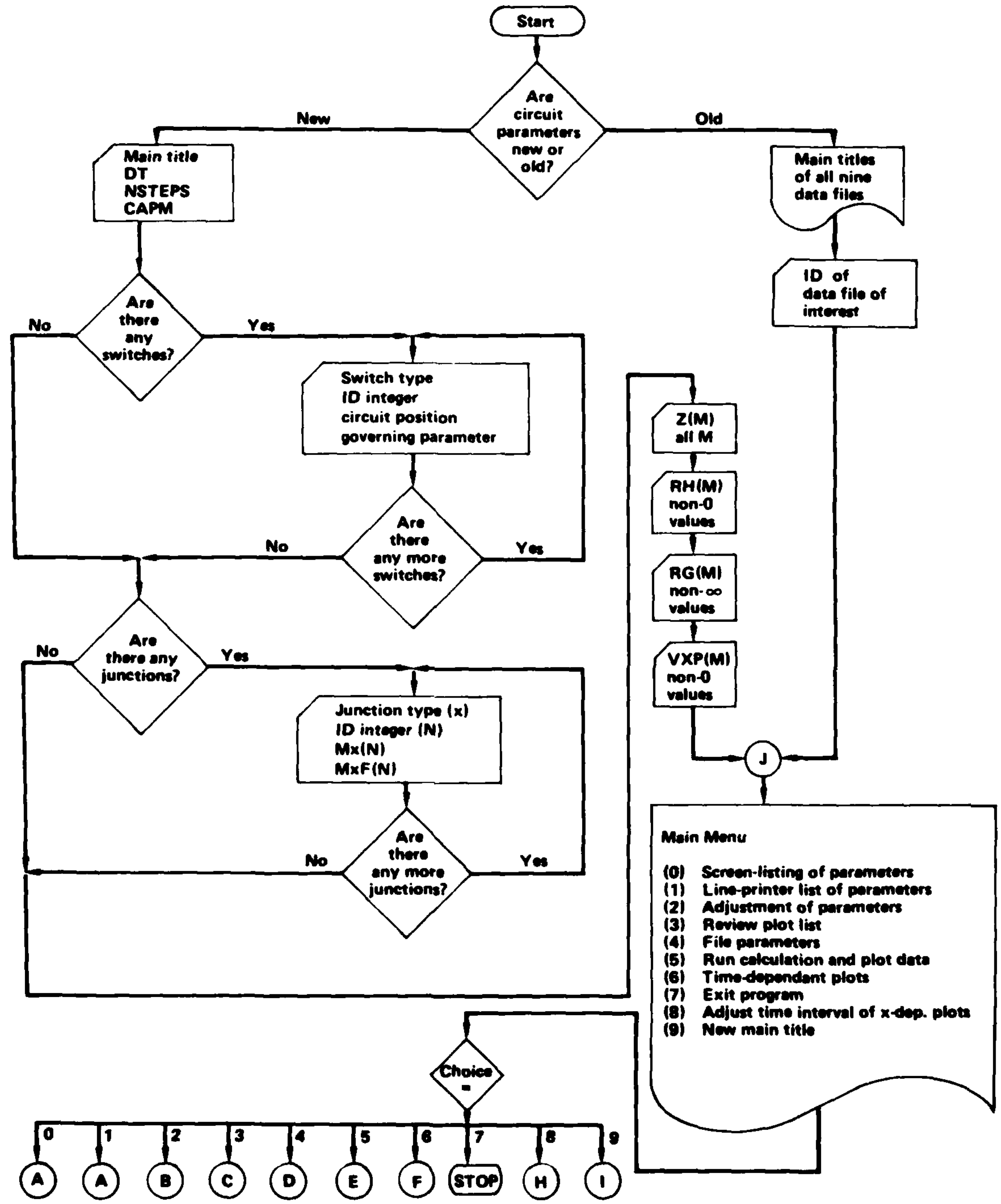
which can be put into the form we desire by noting that DT/Z=C and integrating:

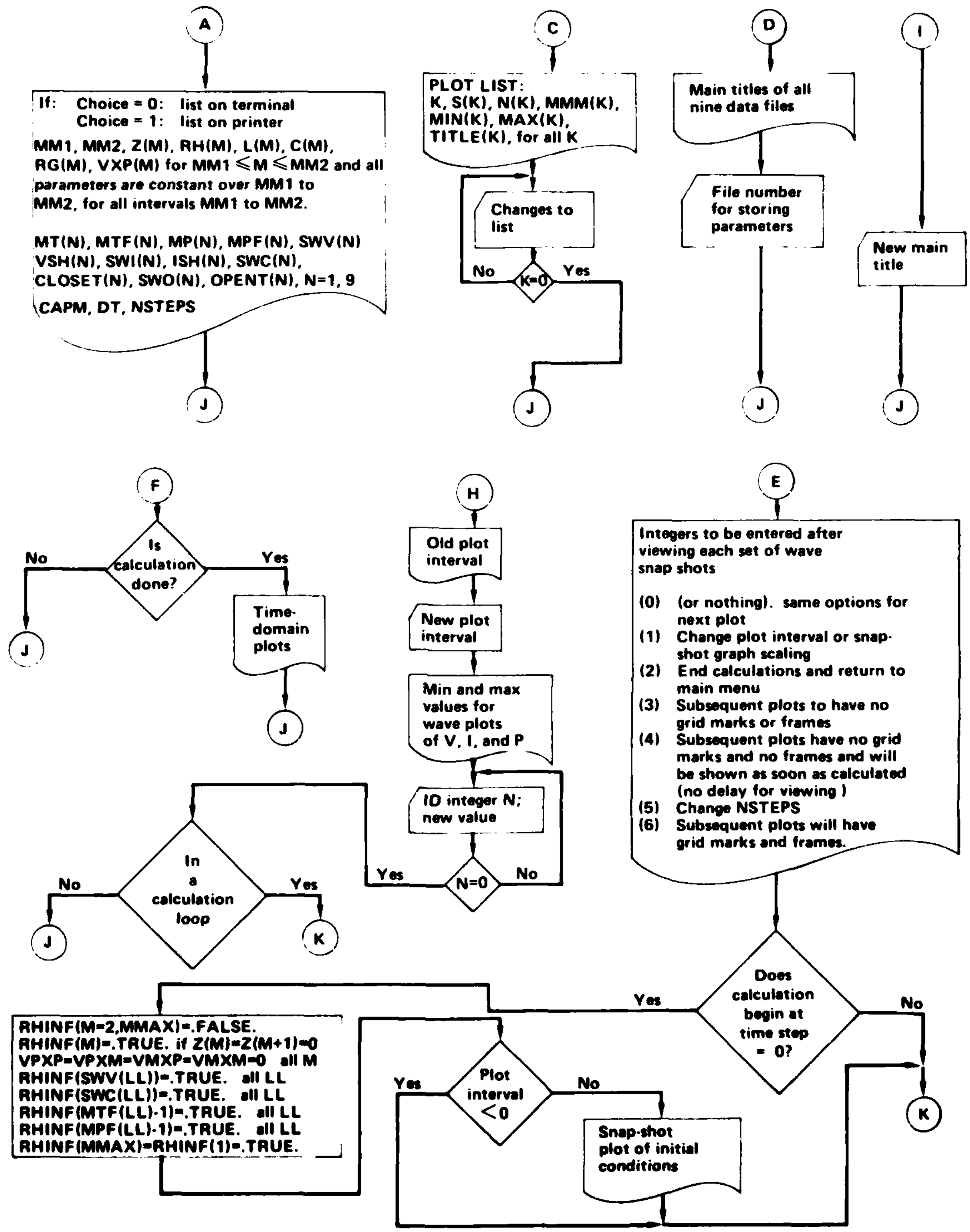
$$V = Q/C. \tag{D-12}$$

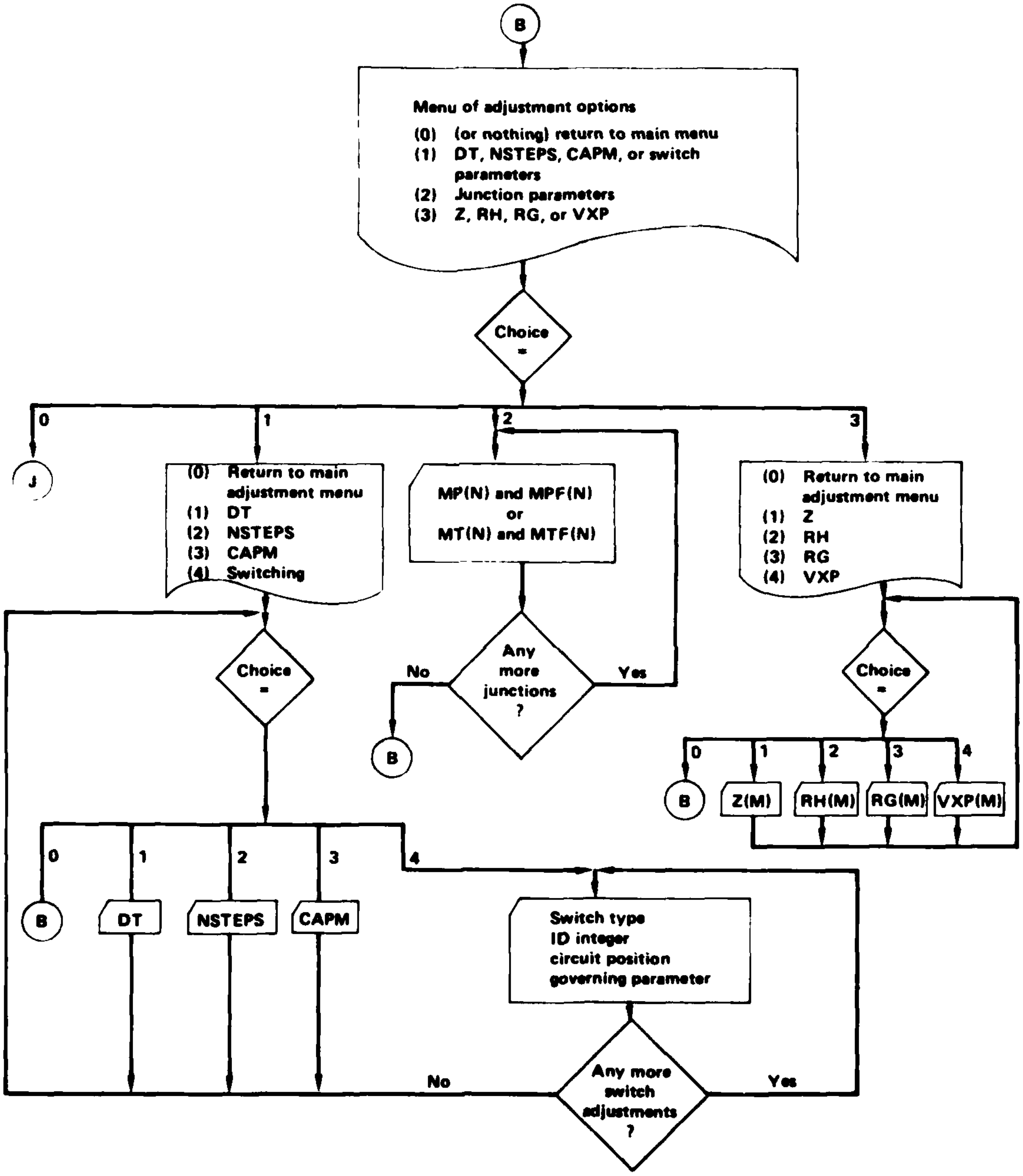
D-3. REMARKS

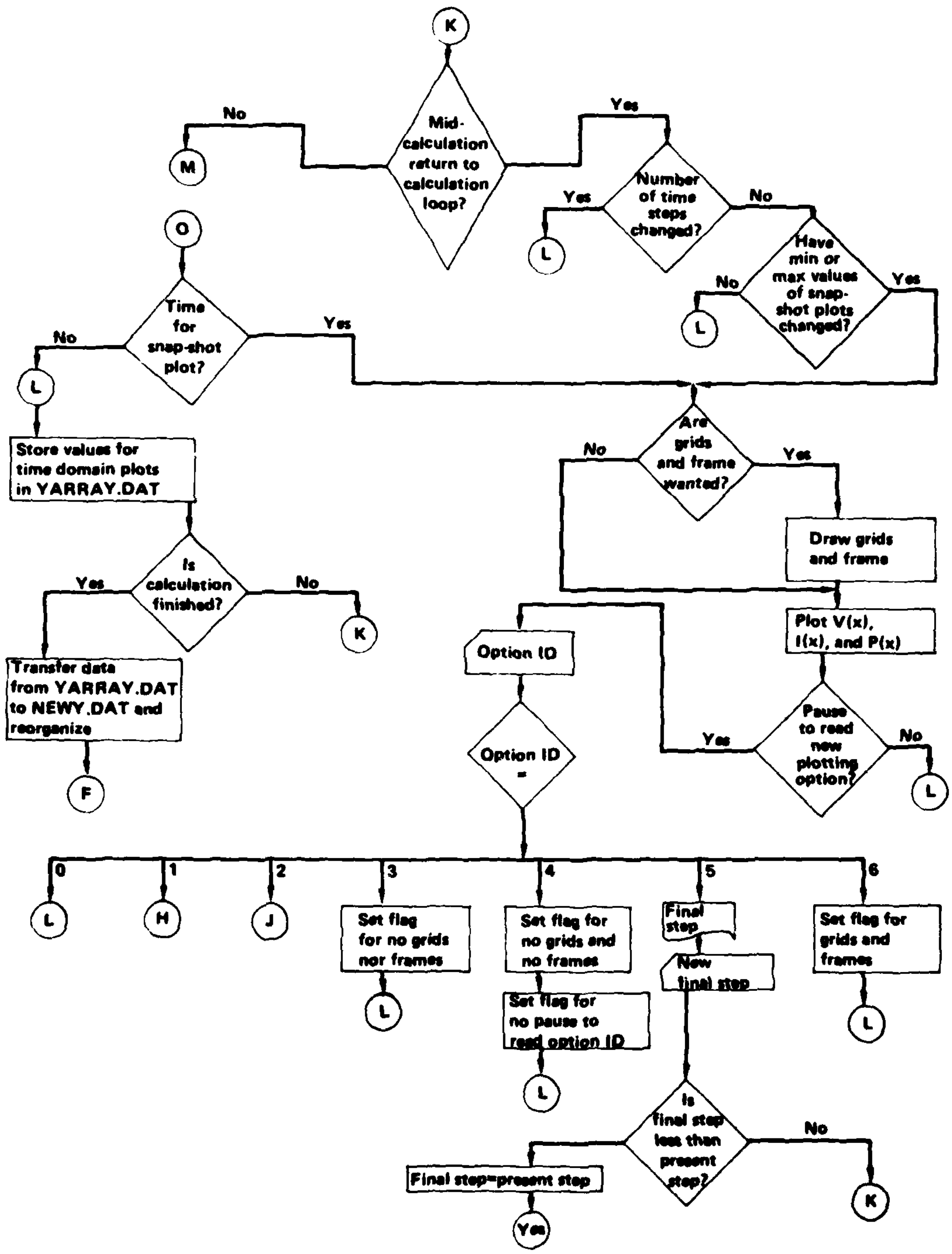
Both equations (D-6) and (D-12) were obtained without assumptions regarding the physical situation of the transmission line and the waves traveling through it. So the transmission line is at once both an inductor and a capacitor. This does not present us with a paradox because the voltage is measured differently when the transmission line is considered to be a capacitor than when it is considered to be an inductor. Whether the transmission line is mostly inductive in its behavior or mostly capacitive depends on the context within which it is used. A comparison of the capacitive and inductive reactances reveals whether the transmission line is capacitive or inductive, and this must be done within the context of the rest of the circuit. A small capacitive reactance $R_c = Z/(DT\omega)$ implies the transmission lines is capacitive, whereas a large inductive reactance $R_L = Z \cdot DT \cdot \omega$ implies the transmission line is inductive.

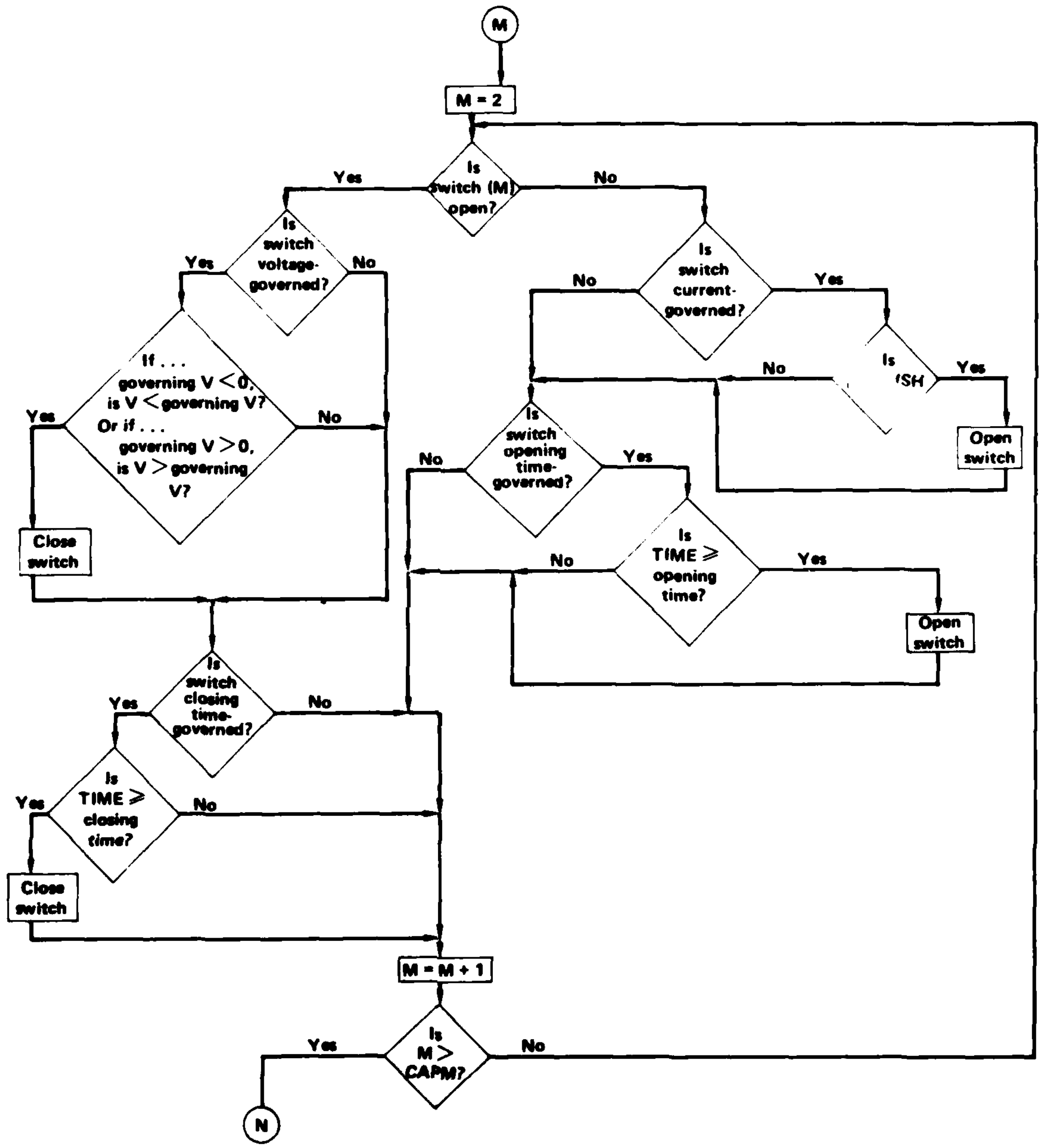
Appendix E.—Flowchart of TLINES

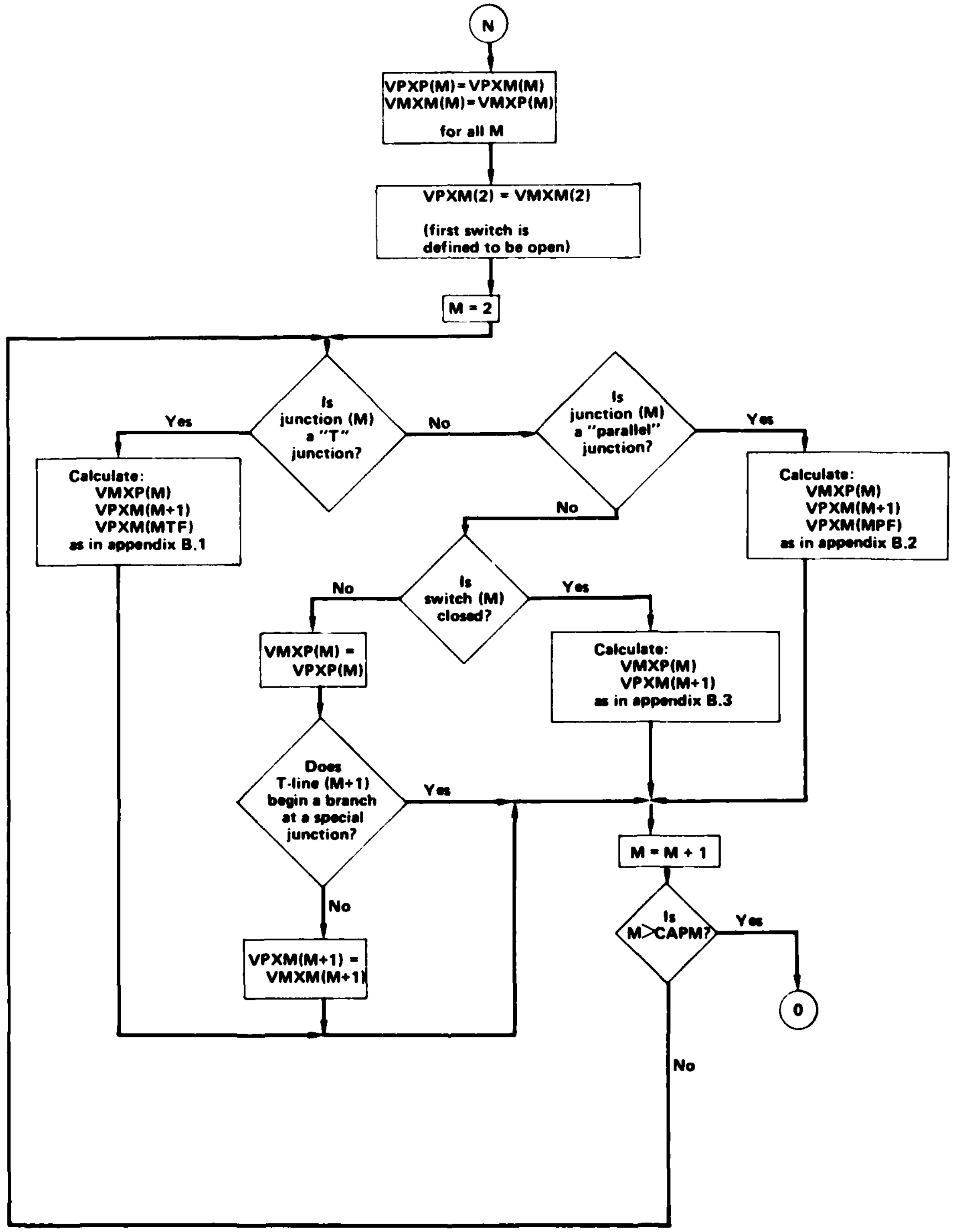

Start
Are circuit parameters new or old?
New
Old
Main title
DT
NSTEPS
CAPM
Main titles of all nine data files
ID of data file of interest
Are there any switches?
No
Yes
Switch type
ID integer
circuit position
governing parameter
Are there any more switches?
No
Yes
Are there any junctions?
No
Yes
Junction type (x)
ID integer (N)
Mx(N)
MxF(N)
Are there any more junctions?
No
Yes
Z(M)
all M
RH(M)
non-0
values
RG(M)
non-∞
values
VXP(M)
non-0
values
J
Main Menu
(0) Screen-listing of parameters
(1) Line-printer list of parameters
(2) Adjustment of parameters
(3) Review plot list
(4) File parameters
(5) Run calculation and plot data
(6) Time-dependant plots
(7) Exit program
(8) Adjust time interval of x-dep. plots
(9) New main title
Choice =
0
1
2
3
4
5
6
7
8
9
A
A
B
C
D
E
F
STOP
H
I


A
If: Choice = 0: list on terminal
Choice = 1: list on printer
MM1, MM2, Z(M), RH(M), L(M), C(M), RG(M), VXP(M) for MM1 ≤ M ≤ MM2 and all parameters are constant over MM1 to MM2, for all intervals MM1 to MM2.
MT(N), MTF(N), MP(N), MPF(N), SWV(N) VSH(N), SWI(N), ISH(N), SWC(N), CLOSET(N), SWO(N), OPENT(N), N=1, 9
CAPM, DT, NSTEPS
J
C
PLOT LIST: K, S(K), N(K), MMM(K), MIN(K), MAX(K), TITLE(K), for all K
Changes to list
No
K=0
Yes
J
D
Main titles of all nine data files
File number for storing parameters
J
I
New main title
J
F
Is calculation done?
No
Yes
J
Time-domain plots
J
H
Old plot interval
New plot interval
Min and max values for wave plots of V, I, and P
ID integer N; new value
Yes
N=0
No
In a calculation loop
No
Yes
J
K
E
Integers to be entered after viewing each set of wave snap shots
(0) (or nothing). same options for next plot
(1) Change plot interval or snap-shot graph scaling
(2) End calculations and return to main menu
(3) Subsequent plots to have no grid marks or frames
(4) Subsequent plots have no grid marks and no frames and will be shown as soon as calculated (no delay for viewing)
(5) Change NSTEPS
(6) Subsequent plots will have grid marks and frames.
Does calculation begin at time step = 0?
Yes
No
K
RHINF(M=2,MMAX)=.FALSE.
RHINF(M)=.TRUE. if Z(M)=Z(M+1)=0
VPXP=VPXM=VMXP=VMXM=0 all M
RHINF(SWV(LL))=.TRUE. all LL
RHINF(SWC(LL))=.TRUE. all LL
RHINF(MTF(LL)-1)=.TRUE. all LL
RHINF(MPF(LL)-1)=.TRUE. all LL
RHINF(MMAX)=RHINF(1)=.TRUE.
Plot interval <0
Yes
No
Snap-shot plot of initial conditions


B
Menu of adjustment options
(0) (or nothing) return to main menu
(1) DT, NSTEPS, CAPM, or switch parameters
(2) Junction parameters
(3) Z, RH, RG, or VXP
Choice =
0
1
2
3
J
(0) Return to main adjustment menu
(1) DT
(2) NSTEPS
(3) CAPM
(4) Switching
MP(N) and MPF(N)
or
MT(N) and MTF(N)
Any more junctions ?
No
Yes
B
(0) Return to main adjustment menu
(1) Z
(2) RH
(3) RG
(4) VXP
Choice =
0
1
2
3
4
B
Z(M)
RH(M)
RG(M)
VXP(M)
Choice =
0
1
2
3
4
B
DT
NSTEPS
CAPM
Switch type
ID integer
circuit position
governing parameter
Any more switch adjustments ?
No
Yes


K
Mid-calculation return to calculation loop?
No
Yes
M
Number of time steps changed?
Yes
No
L
Have min or max values of snap-shot plots changed?
No
Yes
L
O
Time for snap-shot plot?
No
Yes
L
Store values for time domain plots in YARRAY.DAT
Is calculation finished?
Yes
No
K
Transfer data from YARRAY.DAT to NEWY.DAT and reorganize
F
Are grids and frame wanted?
No
Yes
Draw grids and frame
Plot V(x), I(x), and P(x)
Option ID
Option ID =
Pause to read new plotting option?
Yes
No
L
0
1
2
3
4
5
6
L
H
J
Set flag for no grids nor frames
L
Set flag for no grids and no frames
Set flag for no pause to read option ID
L
Final step
New final step
Set flag for grids and frames
L
Is final step less than present step?
No
K
Final step=present step
Yes


M
M = 2
Is switch (M) open?
Yes
No
Is switch voltage-governed?
Yes
No
If . . . governing V < 0, is V < governing V? Or if . . . governing V > 0, is V > governing V?
Yes
No
Close switch
Is switch current-governed?
No
Yes
Is ISH
No
Yes
Open switch
Is switch opening time-governed?
No
Yes
Is TIME ≥ opening time?
No
Yes
Open switch
Is switch closing time-governed?
Yes
No
Is TIME ≥ closing time?
Yes
No
Close switch
M = M + 1
Is M > CAPM?
Yes
No
N


N
VPXP(M) = VPXM(M)
VMXM(M) = VMXP(M)
for all M
VPXM(2) = VMXM(2)
(first switch is defined to be open)
M = 2
Is junction (M) a "T" junction?
Yes
No
Calculate: VMXP(M) VPXM(M+1) VPXM(MTF) as in appendix B.1
Is junction (M) a "parallel" junction?
Yes
No
Calculate: VMXP(M) VPXM(M+1) VPXM(MPF) as in appendix B.2
Is switch (M) closed?
No
Yes
VMXP(M) = VPXP(M)
Calculate: VMXP(M) VPXM(M+1) as in appendix B.3
Does T-line (M+1) begin a branch at a special junction?
Yes
No
VPXM(M+1) = VMXM(M+1)
M = M + 1
Is M>CAPM?
Yes
No
0

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